BACHELOR THESIS AND COLLOQUIUM – ME 141502

TWO STROKES DIESEL ENGINE EXHAUST VALVE STRESS ANALYSIS USING CERAMIC (S_3N_4) COATING

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DEPARTMENT OF MARINE ENGINEERING
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Institut Teknologi Sepuluh Nopember
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DOUBLE DEGREE PROGRAM OF
MARINE ENGINEERING DEPARTMENT
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ANALISA TEGANGAN KATUP GAS BUANG MESIN DISEL 2 LANGKAH MENGGUNAKAN LAPISAN *CERAMIC* (SI_3N_4)

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APPROVAL FORM

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Submitted to Comply One of the Requirement to Obtain a Bachelor of Engineering Degree
On
Laboratory of Marine Manufacturing & Design (MMD)
S-1 Program Department of Marine Engineering
Faculty of Marine Technology
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Department	: Marine Engineering

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ABSTRACT

Exhaust valve is an important part of a diesel engine. Exhaust valve used for control of exhaust gas and seal the combustion chamber. Failure on exhaust valve can affect the performance of the engine. On related journal, present cause of exhaust valve failure namely, fatigue, high temperature, erosion-corrosion, and wear. It found that there is a material able to withstand high temperature (1000^0C) without failure up to 10^7 cycles (more than others common exhaust valve materials) which is ceramic (Si_3N_4). Ceramic can be applied as coating on diesel engine parts (exhaust valve combustion face). Applying ceramic as coating on exhaust valve influenced the stress on exhaust valve during operation, therefore simulation test is required. FEM (Finite Element Method) is used as test tool. The simulation is divided into 3 different load cases (mechanical, thermal, and thermo-mechanical) and based on 4 models which are non-coated exhaust valve and coated with thickness variation of 0.3, 0.4, and 0.5 in mm. The result shown that exhaust valve stress increase with thermo-mechanical load at seat face area (the highest stress occur) by 1.1% (3.96 MPa) on exhaust valve with 0.5mm coating thickness compared to the non-coated exhaust valve.

Keywords: diesel engine, exhaust valve, stress analysis, ceramic coating.

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ANALISA TEGANGAN KATUP GAS BUANG MESIN DISEL 2 LANGKAH MENGGUNAKAN LAPISAN *CERAMIC* (SI_3N_4)

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ABSTRAK

Katup gas buang merupakan komponen penting pada mesin disel. Katup gas buang berfungsi untuk mengatur aliran gas buang serta menjaga kekedapan pada ruang bakar. Kerusakan pada katup gas buang dapat berakibat fatal pada kinerja mesin disel. Pada penelitian sebelumnya disebutkan ada 4 penyebab terjadinya kerusakan pada katup gas buang yaitu *fatigue*, temperatur tinggi, erosi-korosi, dan goresan. Pada penelitian tersebut juga ditemukan ada material yang tahan terhadap suhu tinggi (1000^0C) sampai dengan 10^7 siklus (lebih tinggi dibandingkan material katup gas buang pada umumnya) yaitu keramik (Si_3N_4). Keramik dapat digunakan sebagai lapisan pada komponen mesin disel. Penggunaan lapisan keramik dapat berdampak pada tegangan yang diterima oleh katup gas buang, sehingga diperlukan pengujian untuk mengetahuinya. Pengujian dilakukan dengan metode *Finite Element* (FE). Pengujian terbagi menjadi 3 kasus beban (*mechanical load*, *thermal load*, dan *thermo-mechanical load*) serta berdasarkan 4 model yaitu katup gas buang tanpa lapisan dan menggunakan lapisan dengan ketebalan 0.3mm, 0.4mm, dan 0.5mm. Hasil akhir menunjukkan adanya peningkatan tegangan pada beban *thermo-mechanical* di area *seat face* (lokasi tegangan terbesar) sebesar 1.1% (3.96 MPa) pada katup gas buang dengan ketebalan lapisan sebesar 0.5mm dibandingkan dengan tanpa lapisan (standar).

Kata kunci: mesin disel, katup gas buang, analisa tegangan, lapisan keramik.

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PREFACE

Alhamdulillahirabbil 'alamin, huge thanks to Allah SWT the God Almighty for giving intelligent, strength, health and favours so the author can finish this bachelor thesis.

This bachelor thesis aims to know stress distribution and effect of ceramic coat on exhaust valve diesel engine. The author also would express his immeasurable appreciation and deepest gratitude for those who helped in completing this Bachelor Thesis:

1. The author's parents Bapak Suliyo and Ibu Wartini, author's siblings, and the whole family who have always given motivation and unceasingly prayer.
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8. Author's beloved partner Arsya Sita Mianda Putri who has given motivation, suggestion, and support while author confused and remind to stay focus to finish this bachelor thesis.

The author realizes that this thesis remains far away from perfect. Therefore, every constructive suggestions and idea from all parties are highly expected by the author to improve this bachelor thesis in future. Hopefully, this bachelor thesis can be advantages for all of us, particularly for the readers.

Surabaya, July 2017.
Author

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CHAPTER I
INTRODUCTION

1.1. Background

Diesel engines use air compression to ignite the fuel produced by piston movement, because of this diesel engine works at high pressure and high temperature. Diesel engine used at ship are commonly operating for a long-term period (days), this can lead to cause engine failure because of high temperature and high pressure produced in the combustion chamber. Combustion chamber is the location of air being compressed and fuel being burned. Combustion chamber parts are consist of cylinder liner, cylinder head (exhaust valve combustion face), and piston crown.

One of all engine failure causes especially exhaust valve is due to fatigue. Fatigue in exhaust valve is because of the exhaust valve repeatedly received load (high pressure and high temperature). Repeated of high load results in materials strength failing into below the yield strength. When the material is subjected to fatigue, one or more tiny cracks usually start developing in the material, and these grow until complete failure occurs. (Raghuwanshi, Pandey, & Mandloi, 2012)

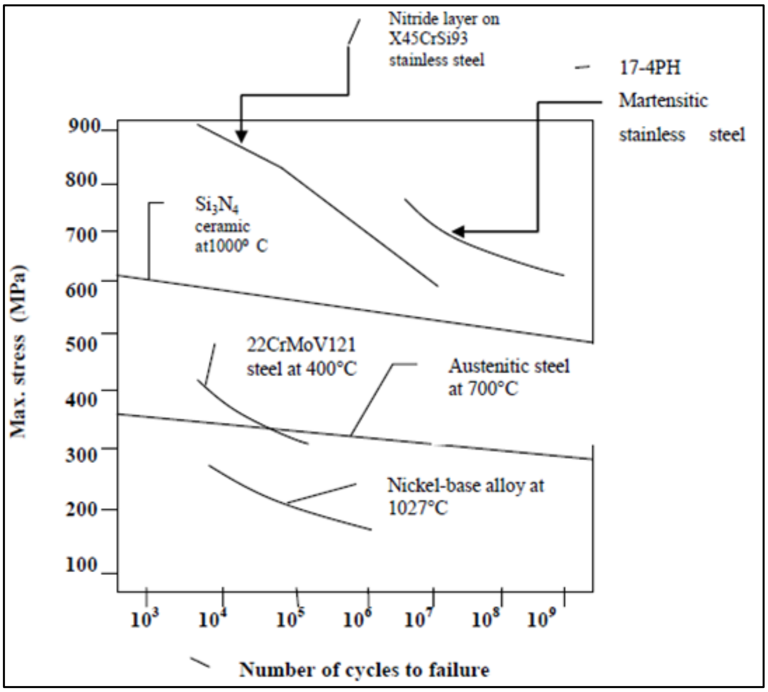

Figure 1. 1 S-N Curve for Different Materials Engine Valve at High Temperature (Raghuwanshi, Pandey, & Mandloi, 2012)

Previous research (Raghuwanshi, Pandey, & Mandloi, 2012) analyzes the failure of internal combustion engine valves. There are different type cause of failure namely: fatigue, high temperature (thermal stress), erosion-corrosion, and wear. Exhaust valve on those research is made of stainless steel composition (X45CrSi93). From Figure 1. 1 shows the S-N curve for different materials. The X45CrSi93 failed when 10^7 cycles, but there is material do not failure up to 10^9 cycle operation which is ceramic Si_3N_4. Si_3N_4 is one of ceramic advance technology.

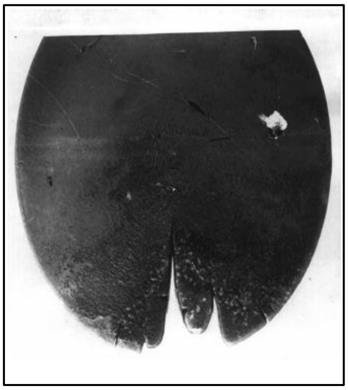

Figure 1. 2 Fracture Plate of Exhaust Valve (Yu & Xu, 2005)

The focus of this bachelor thesis is stress analysis on exhaust valve two strokes diesel engine. Applied stresses on exhaust valve are thermal and mechanical stress. Thermal stress comes from exhaust gas temperature. Effect of high temperature in the combustion chamber can lead damage of exhaust valve combustion face (plate), it can be seen in Figure 1. 2. To overcome those problems coating with higher strength material such as ceramic can be applied. Application of ceramic material on diesel engines can be as a coating layer on combustion chamber parts such as piston crown, cylinder liner, and exhaust valve combustion face. Effect of ceramic coating in previous research on combustion chamber parts is increasing the thermal efficiency of engines because ceramic coating reduced heat loss or heat dissipation in the combustion chamber. (Civiniz, Mustafa, Kose, Canli, & Solmaz, 2012)

The effect of Si_3N_4 coating on exhaust valve stress can be shown by conduct simulation using FEM (Finite Element Method). Ceramic coating will be applied on combustion face with thickness variation. The engine that will be used on this bachelor thesis is two strokes diesel engine and the required material are nimonic 80A (base material) & ceramic Si_3N_4 material as a coating layer.

1.2. Problems Statement

1. How the stress distribution of exhaust valve (non-coated Nimonic 80A) of a two-stroke diesel engine?
2. How the stress distribution of exhaust valve using Ceramic (Si_3N_4) coating?
3. How the effect of Ceramic (Si_3N_4) coating on exhaust valve stress?

1.3. Research Scope

1. Exhaust valves condition for simulation: non-coating, 0.3mm ceramic coated, 0.40mm ceramic coated, and 0.50mm ceramic coated.
2. The coating is only applied on combustion face of the exhaust valve (refer to the previous journal).
3. Using two-stroke diesel engine as a sample of diesel engine.
4. Assume that the diesel engine is 100% in good condition (new built).
5. Simulation conduct in 100% load and 100% rpm of the engine.

1.4. Research Objectives

1. To know the stress distribution on two-strokes diesel engine exhaust valve (non-coated nimonic 80A).
2. To know the stress distribution on the exhaust valve using ceramic (Si_3N_4) coating.
3. To know the effect of ceramic (Si_3N_4) coating on exhaust valve stress.

1.5. Research Benefits

1. Knowing the stress distribution in non-coating exhaust valve of two-stroke diesel engine
2. Knowing the stress distribution and effect of the ceramic coating layer on exhaust valve of a two-stroke diesel engine.

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CHAPTER II
LITERATURE STUDY

2.1. Diesel Engine Data and Performance

2-strokes diesel engine used as main engine for ship propulsion. The 2-strokes diesel engine has lower rpm (rotation per minute) than 4-strokes diesel engine and has bigger size than a 4-strokes diesel engine. It is commonly used for cargo ship (such as container vessel, bulk carriers, tankers, etc.) because it has a big power. This engine has a variation of power output with the number of cylinders from 5 to 12 cylinders. This two-stroke diesel engine has specification as follow:

- Bore : 350 mm
- Stroke : 1050 mm
- Maximum exhaust gas temperature : 420^{0}C
- Maximum cylinder pressure : 140 bar

Table 2.6 Power and Speed of 2-strokes Diesel Engine (MAN Corporation, 2009)

Layout points	Engine Speed (r/min)	Power (kW)							
		Number of cylinders							
		5	6	7	8	9	10	11	12
L_1	210	3250	3900	4550	5200	5850	6500	7150	7800
L_2	210	2600	3120	3640	4610	4680	5200	5720	6240
L_3	178	2750	3300	3850	4400	4950	5500	6050	6600
L_4	178	2200	2640	3080	3520	3960	4400	4840	5280

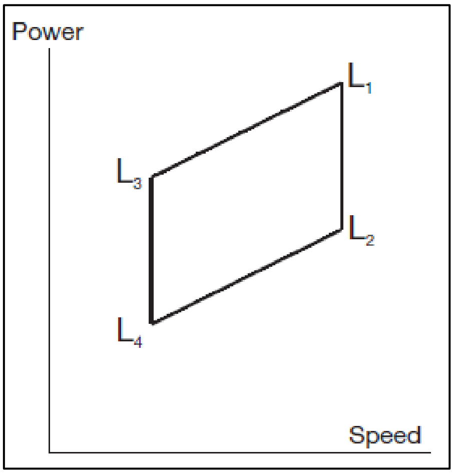


Figure 2. 1 Power-Speed Layout Diagram (MAN Corporation, 2009)

On Figure 2. 1 shows L_1 designates nominal maximum continuous rating (nominal MCR) at 100% engine power and 100% engine speed. L_2, L_3, and L_4 designate layout points at the other three corners of the layout area, chosen for easy reference. (MAN Corporation, 2009)

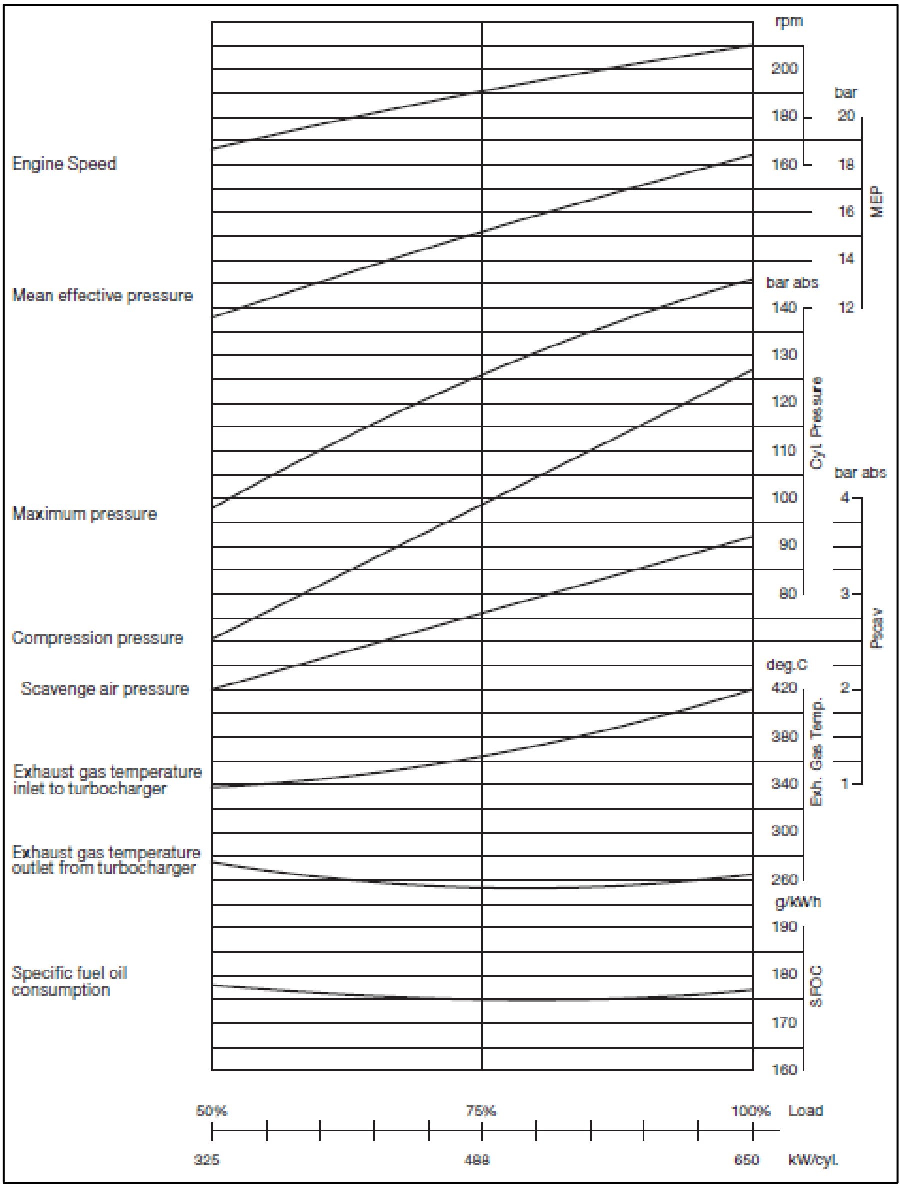


Figure 2. 2 Performance Curves (MAN Corporation, 2009)

Performance curves indicate the output of engine with different load (power) of each cylinder. Performance curves are consist of engine speed, mean effective pressure, maximum pressure, compression pressure, scavenge air pressure, exhaust gas temperature in inlet and outlet of the turbocharger, and also Specific Fuel Oil Consumption (SFOC). From the Figure 2. 2, it can be seen that the temperature of the exhaust gas that enters the turbocharger is from 340^{0}C up to 420^{0}C and pressures in each cylinder is from 75 to 125 bar absolute with a maximum limit from 100 to 145 bar absolute. Data on that figures are taken when the engine is operated with load variation from 50% until 100% load.

2.2. Exhaust Valve

Valves that used in internal combustion engines are: 1. Poppet valves; 2. Rotary valves; 3. Sleeve valve. The poppet valve is commonly used. The poppet valve is consist of head and stem. The seat face angle varies from 30^0 to 45^0 generally. The poppet valve derives its name from its popping movement up and down. This is also known as mushroom valve because of its shape which is similar to a mushroom. (Sanoj & S, 2012)

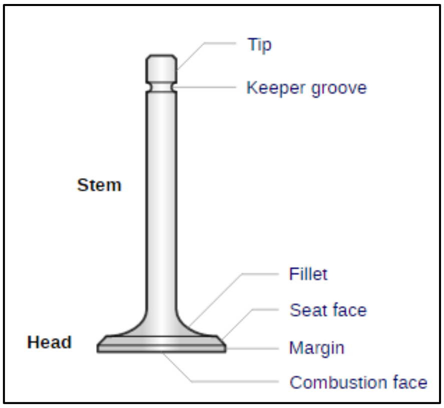


Figure 2. 3 Exhaust Valve Nomenclature (Voorwald, Coisse, & Cioffi, 2011)

In 2-strokes diesel engine only has one type of valve which is exhaust valve. Exhaust valve in a 2-stroke diesel engine is located in the center of cylinder head. On the conventional type of exhaust valve, the close-open movement is controlled by cam rotation located in the camshaft. That cam will push the push rod, where the push rod will move the rocker arm and then open the exhaust valve. To close the exhaust valve, this type is used valve spring that attached in the valve stem. On this type, there is a disadvantage which is will cause wear in valve stem which leads to crack in valve stem. In order to overcome the problems associated with rocker actuation of exhaust valves, hydraulic actuation was introduced. (Anonym, n.d.)

On Figure 2. 3, shown that exhaust valve is consist of some parts which are: stem, seat face, combustion face, and keeper groove. Seat face is part of exhaust valve that direct contacts with valve seat. On this area normally there are some deposits from combustion products which can be harmful to seat face because it is corrosive, furthermore this deposits can be added stress in seat face when exhaust valve closed. Combustion face is part or surface of exhaust valve which received the highest thermal and mechanical load since it directly contacted with the combustion chamber.

2.2.1. Exhaust valve load

The exhaust valve is main parts of exhaust gas system as controller of exhaust gas flow from the combustion process. As we already discussed before, exhaust valve works at high temperature and high pressure. Pressure and temperature of the gas in combustion chamber can reach higher than 200 bars and 1600^0K (See Figure 2. 4). Parts of exhaust valve which directly contact with combustion chamber is combustion face. Therefore material that can withstand the high temperature and high pressure is needed.

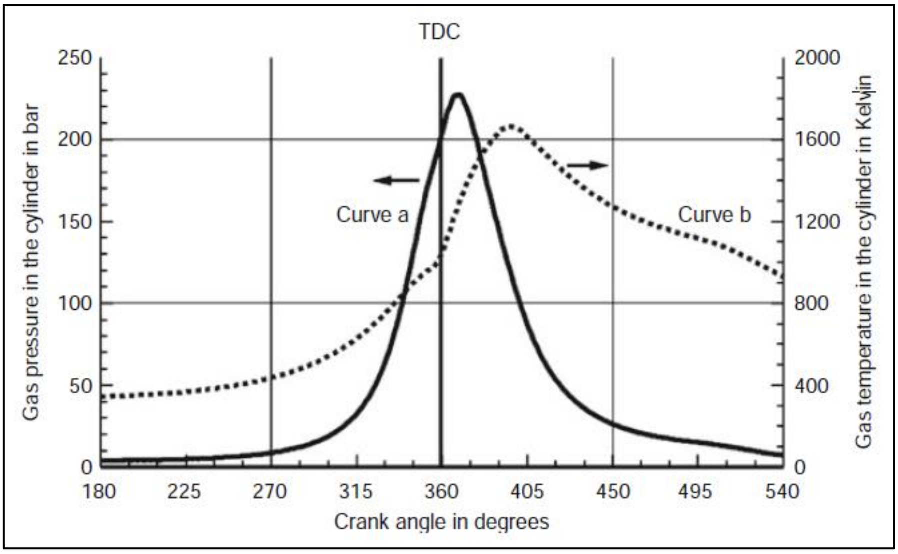


Figure 2. 4 Time Characteristic of Gas Pressure (Curve A) and the Average Gas Temperature (Curve B) for a Medium Speed 4-Stroke Engine (Mollenhauer & Tschoeke, 2009)

2.2.1.1. Thermal load

In a diesel engine, the thermal load is related to temperature change due to exhaust gas that produces from combustion process. Exhaust gas flows through exhaust gas system. Exhaust gas system is started from exhaust valve that located in cylinder head which used to control exhaust gas stream into exhaust gas port (cage). However, not all exhaust valve parts are passed by exhaust gas. So, this different temperature distribution could cause thermal stress in exhaust valve, especially in valve head area because this area receives higher temperature than another area of the exhaust valve.

Thermal stress distribution in exhaust valve can be seen in Figure 2. 5. In this figure, shown valve head are receive thermal load (temperature) higher than other parts. It is caused on those parts is directly contacted with the combustion chamber and not cooled by cooling system as other parts which are contact with cooled parts. Seat face has lower temperature because it is contacted with the cooled valve seat.

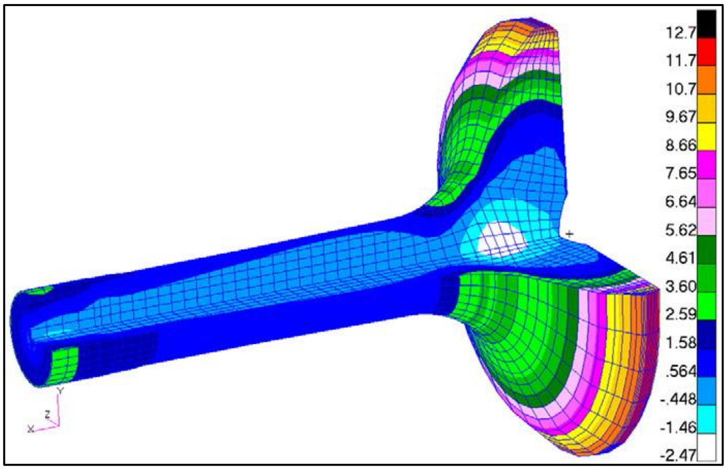


Figure 2. 5 Thermal Stress Distribution (Witek, 2016)

Thermal stresses are stresses induced in a body as a result of a change in temperatures. The magnitude of the stress σ resulting from a temperature change from T_0 to T_1 is:

$$\sigma = E\varepsilon = E\alpha_l(T_0 - T_1) = E\alpha_l\Delta T$$

Equation 2. 1

Where:

σ : thermal stress (Pa, N/m^2)
E : modulus of elasticity (N/m^2)
ε : strain (m/m)
α : linear coefficient of thermal expansion (m/m^0C)
T_0 : initial temperature (^0C)
T_1 : initial temperature (^0C)

2.2.1.2. Mechanical load (compression)

Mechanical load on exhaust valve mainly come from compression in the combustion chamber. Compression is produced from piston movement that compressed air which goes into the combustion chamber via inlet port. Pressure that produced from compression depends on the compression ratio of each engine, normally compression ratio for a diesel engine is from 15 to 20 (Nave, 2016). Figure 2. 6 shows load from valve spring will cause stress on exhaust valve parts especially on fillet area (between the stem and valve head) when the exhaust valve closed.

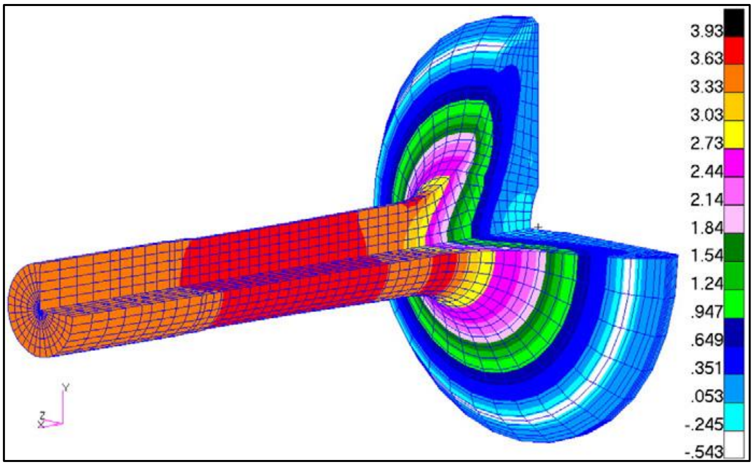


Figure 2. 6 Stress Distribution Cause by Valve Spring and Cylinder Pressure (Witek, 2016)

- Normal stress caused by force is defined as:

$$\sigma = \frac{F}{A}$$

Equation 2. 2

Where:

P : force or load (N)
A : sectional area of the plane (m^2)
σ : stress (Pa, N/m^2)

- Compressive stress is can be calculated with formula:

$$\sigma = -\frac{\Delta l}{l_0}E = -\varepsilon E$$

Equation 2. 3

Where:

σ : stress (Pa, N/m^2)
Δl : deformation (m)
L_0 : initial length (m)
E : young modulus (N/m^2)
ε : strain (m/m)

- Tensile stress is can be calculated with formula:

$$\sigma = \frac{\Delta l}{l_0}E = \varepsilon E$$

Equation 2. 4

Where:

σ : stress (Pa, N/m^2)
Δl : deformation (m)
L_0 : initial length (m)

E : young modulus (N/m^2)
ε : strain (m/m)

2.2.2. Exhaust valve failure

Mostly failure on exhaust valves are due to exhaust valve is working at high temperature, high pressure, and tensile load from valve spring. Temperature distribution on exhaust valve in accordance with Figure 2. 5, combustion face area and lower part of valve stem has a higher temperature than another area.

Pressure from inside the cylinder produced by compression and combustion process also contribute stress on the exhaust valve, especially at valve head part. On seat face of exhaust valve will have compression stress, because that part is directly contacted with a valve seat which sustained by cylinder head (rigid body). Thermal stress (stress due to temperature change) also contribute to exhaust valve failure. Increasing of temperature caused expansion of exhaust valve which can lead to addition compression stress at seat face area. As a result of compression and thermal stress, failure can occur at seat face area as can be seen in **Error! Reference source not found.**9.

Figure 2. 7 Exhaust Valve Seat Face Failure (VARDAR & EKERIM, 2009)

Another exhaust valve failure is due to tensile stress caused by valve spring. Valve spring functioned to lift and keep exhaust valve in the closed position when compression and combustion process. Lifting force of valve spring caused compression stress and also tensile stress. Compressive stress occurs on seat face area. Meanwhile, tensile stress occurs at fillet and valve stem parts. Exhaust valve failure due to high temperature can be seen in Figure 2. 7, valve stem part receives higher temperature since exhaust gas flow directly through that area and receives a tensile load from valve spring which caused failure on valve stem. Exhaust valve failure can be seen in Figure 2. 8.

On that figure, there is a fracture on valve stem (A) and fillet area of exhaust valve (B).

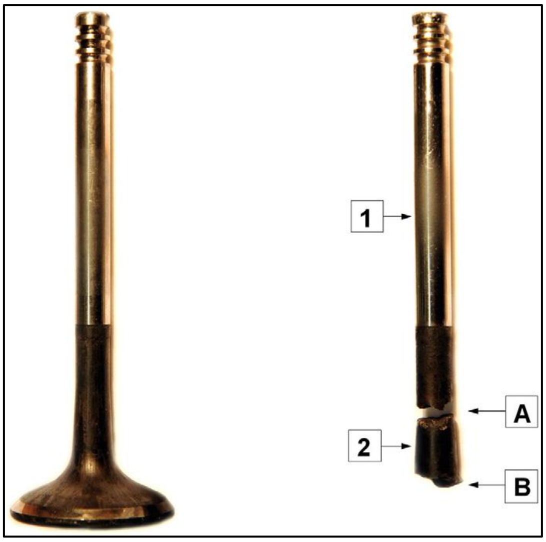


Figure 2. 8 Valve Stem Failure (Witek, 2016)

Failure on exhaust valve can affect the engine performance and moreover damage the engine. One of the damages caused by exhaust valve failure is on piston crown as in the figure below (Figure 2. 9). It can be seen there is damage on piston crown caused by fracture of exhaust valve fall into the combustion chamber and then stick on the piston.

Figure 2. 9 Damaged Piston with the Piece of Fractured Valve (Witek, 2016)

2.3. Material of Exhaust Valve

Diesel engine or commonly called as Internal Combustion (I.C.) is engine that works at high temperature and high pressure. The temperature of exhaust gas from combustion process normally can shoot up to 420°C and pressure of 140 bars absolute in full load condition (MAN B&W L35MC6). Therefore, high material qualities are required to withstand high temperature and high pressure. To fulfill the requirement, exhaust valve must have specification as follows (Sanoj & S, 2012):

1. Sufficient strength and hardness to resist tensile forces and wear
2. Adequate fatigue strength
3. High creep strength
4. Resistance to corrosion
5. Resistance to oxidation at the high operating temperatures
6. Small coefficient of thermal expansion to avoid excessive thermal stresses
7. High thermal conductivity for good heat dissipation

According to Figure 2. 10, there are 2 types of exhaust valve in diesel engine, namely: hollow stem and non-hollow stem. The difference is the construction which used. On this bachelor thesis, the author will use exhaust valve with non-hollow type. On this type, there are two materials which used, Martensitic steel (X45CrSi93) and Nickel alloy (NiCr20TiAl). Welding is needed to join this two material, the material will weld on each end with friction welding methods.

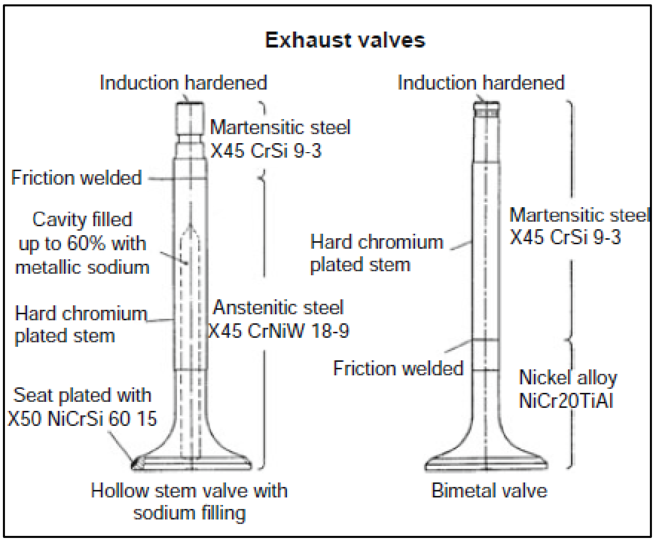


Figure 2. 10 Exhaust Valve Material (Mollenhauer & Tschoeke, 2009)

Materials commonly used as an exhaust valve on a diesel engine are Martensitic Steel X45CrSi93, Nimonic 80A, and 21-4N. On this bachelor thesis, the author will analyze the stress distribution of exhaust valve two-stroke diesel engine with a composition between nimonic 80A as base materials with coating layer using ceramic material with grade Si_3N_4. Here are some specifications of nimonic with grade 80A and also ceramic material with grade Si_3N_4 that obtained from several sources:

2.3.1. Nimonic 80A

Exhaust valve material of the two-stroke diesel engine is nimonic 80A. Nimonic 80A is ductile material (Figure 2. 11). Since it is ductile material, Nimonic 80A has yield strength and tensile strength (ultimate strength). Yield strength used to calculate safety factor of ductile material. Nimonic 80A alloy is a nickel-chromium alloy that is strengthened by the additions of titanium and aluminum. It has high tensile and creep-rupture properties at temperatures up to 815°C (1500°F).

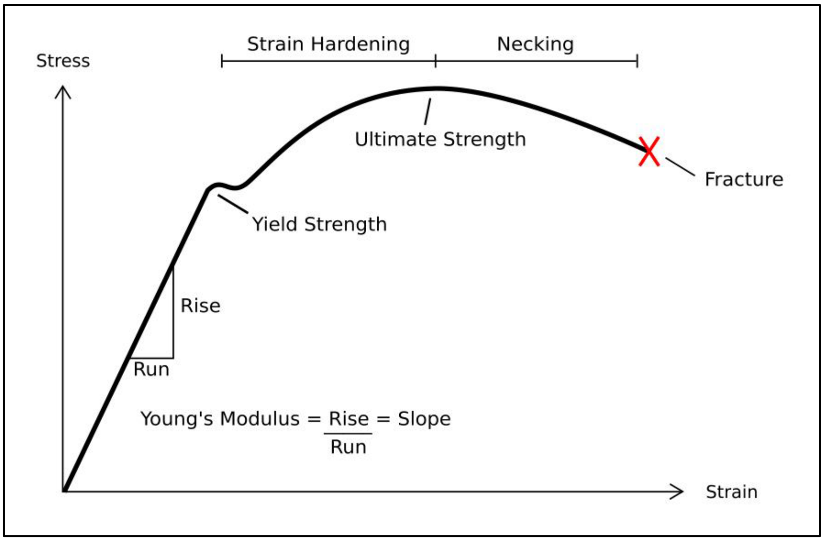


Figure 2. 11 Ductile Material Stress-Strain Diagram

The applications of nimonic 80A are gas turbine components, nuclear steam generators, die-casting inserts and cores, and also exhaust valves in internal combustion engines. The following is properties of nimonic 80A on Table 2. 1 and Table 2. 2:

A. Super Alloy Nimonic 80A (UNS N07080)

Table 2. 1 Nimonic 80A Properties (AZoM, 2013)

Properties	**SI**	**SI**
Physical		
Density	g/cm^3	8.19
Melting point	^0C	1320-1365
Mechanical		
Tensile strength	MPa	1250
Yield strength	MPa	780
Elongation at break	-	30%

Properties	SI	SI
Thermal		
Thermal Conductivity	W/m*°K	11.2
Coefficient of Thermal Expansion	10^{-6}m/m°C	12.7

B. Special Metals Nimonic Alloy 80A

Table 2. 2 Nimonic 80A Properties (MatWeb Material Property Data, 2017)

Properties	SI	SI
Physical		
Density	g/cm^3	8.19
Mechanical		
Tensile Strength, Ultimate	MPa	1250
	MPa	1030
Tensile Strength, Yield	MPa	780
	MPa	710
Elongation at break	-	30%
Thermal		
Thermal Conductivity	W/m*°K	11.2
Coefficient of Thermal Expansion	10^{-6}m/m°C	12.7
Melting point	^{0}C	1320-1365
Solidius	^{0}C	1320
Liquidius	^{0}C	1365

2.3.2. Ceramic (Si_3N_4)

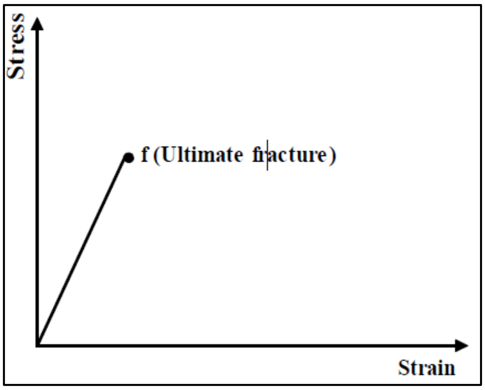


Figure 2. 12 Brittle Material Strain-Stress Diagram

Ceramic (Si_3N_4) is material that can sustain in high pressure and high pressure, so this material is compatible if it is used as a coating on exhaust valve diesel engine. Some applications of ceramic (Si_3N_4) material are internal combustion engine parts, cutting tools, gas turbine parts, bearing, etc. (Adams, 2016). Ceramic is brittle material. Since it is brittle material, ceramic has not yield strength Figure 2. 12. Ultimate strength is used to calculate safety factor. Specification of ceramic (Si_3N_4) material from some source are as follows:

A. CeramTec SL 200 ST Silicon Nitride

Table 2. 3 Ceramtech SL 200 ST Material Properties (MatWeb Material Property Data, 2017)

Properties	SI	SI
Physical		
Density	g/cc	3.21
Weibull Modulus		15
Mechanical		
Vickers Microhardness		1500
Tensile Strength, Ultimate	MPa	750
Tensile Modulus	GPa	305
Flexural Strength	MPa	900
Compressive Strength	MPa	3000
Poisson Ratio		0.26
Fracture Toughness	MPa-m$^{1/2}$	7.00
Shear Modulus	GPa	121
Thermal		
Thermal Conductivity	W/m*°K	21
Coefficient of Thermal Expansion	10^{-6}m/m°C	3.2
Specific Heat Capacity	J/g^{0}C	0.700
Maximum Service Temperature, Air	^{0}C	1300
Maximum Service Temperature, Inert	^{0}C	1600

B. Silicon Nitride (Si_3N_4) Properties

Table 2. 4 Silicon Nitride (Si3N4) Properties (AZoM, 2016)

Property	Minimum Value (S.I.)	Maximum Value (S.I)	Units (S.I.)
Atomic Volume (average)	0.0058	0.006	m^3/kmol
Density	2.37	3.25	Mg/m^3
Energy Content	150	200	MJ/kg
Bulk Modulus	120	241	GPa
Compressive Strength	524	5500	MPa
Ductility	0.00031	0.00169	
Elastic Limit	60	525	MPa
Endurance Limit	44	470	MPa
Fracture Toughness	1.8	6.5	MPa.m$^{1/2}$
Hardness	8000	30500	MPa
Loss Coefficient	2e-005	5e-005	
Modulus of Rupture	181	1050	MPa
Poisson's Ratio	0.23	0.28	
Shear Modulus	65.3	127	GPa
Tensile Strength	60	525	MPa
Young's Modulus	166	297	GPa

Property	Minimum Value (S.I.)	Maximum Value (S.I)	Units (S.I.)
Latent Heat of Fusion	930	1550	KJ/kg
Maximum Service Temperature	1346	1773	K
Melting Point	2661	2769	K
Minimum Service Temperature	0	0	K
Specific Heat	673	1100	J/kg.K
Thermal Conductivity	10	43	W/m.K
Thermal Expansion	1.4	3.7	10^{-6}/K
Breakdown Potential	16	20	MV/m
Dielectric Constant	9.5	10.5	
Resistivity	1e+016	1e+021	10^{-8}ohm.m

2.4. Coating

Thermal barrier coating is commonly used ceramic coating on piston crown, cylinder heads and intake/exhaust valves (on combustion face). When cylinder walls are intended to be coated, a material should be selected which has proper thermal dilatation and wear resistance. Some ceramic materials have self-lubrication properties up to 870°C (Hocking, Vasatasree, & Sidky, 1989).

In Figure 2. 13, energy balance diagrams for conventional diesel engine and ceramic coated engine are given. Besides these advantages of ceramic coated low heat rejection engines, mechanical improvements also gained by lightweight ceramic materials. By their high-temperature resistance and light weight, moving parts of the engine have more duration due to low inertia and stable geometry of the parts. (Civiniz, Mustafa, Kose, Canli, & Solmaz, 2012)

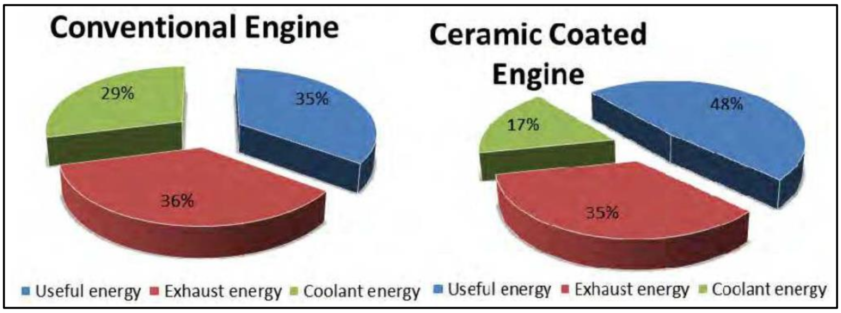


Figure 2. 13 Energy Balance Illustration for Conventional Engine and Ceramic Coated Engine (Civiniz, Mustafa, Kose, Canli, & Solmaz, 2012)

Advantages of ceramic advanced technology can be listed as below (Civiniz, Mustafa, Kose, Canli, & Solmaz, 2012):

1. Resistant to high temperatures
2. High chemical stability
3. High hardness value
4. Low densities
5. Can be found as raw material form in environment
6. Resistant to wear
7. High compression strength

There are several ceramic advanced technologies, namely: alumina (Al_2O_3), Zirconia (ZrO_2), Magnesia (MgO), Berillya (BeO) and non-oxides ones. These advanced technology ceramic properties are given in Table 2. 5.

Table 2. 5 Some Advanced Technology Ceramic Properties (Civiniz, Mustafa, Kose, Canli, & Solmaz, 2012)

Material	Melting Temperature (^{0}C)	Density (g/cm^3)	Strength (MPa)	Elasticity Module (GPa)	Fracture Toughness (MPa/m^2)	Hardness (kg/mm^2)
SiO_2	500	2.2	48	7.2	0.5	650
Al_2O_3	2050	3.96	250-300	36-40	4.5	1300
ZrO_2	2700	5.6	113-130	17-25	6-9	1200
SiC	3000	3.2	310	40-44	3.4	2800
Si_3N_4	1900	3.24	410	30-70	5	1300

Ceramic coatings which applied to reduce heat transfer are divided into two groups. Generally, up to 0.5 mm coatings named as thin coatings and thick coatings are up to 5-6 mm. Ceramic coating with thickness up to 0.5 mm are used in gas turbines, piston tops, cylinder heads and valves of otto and diesel engines. Here are several ceramic coating methods for thin and thick coating (Civiniz, Mustafa, Kose, Canli, & Solmaz, 2012):

- Thermal spray coating: plasma spray, wire flame spray and powder flame spray, electrical arc spray, detonation gun technique and high-speed oxy fuel system
- Chemical ceramic coating: Sole-gel, slurry, chemical vapor sedimentation, physical, vapor sedimentation, hard coating
- Laser coating
- Arc spark alloying
- Ion enrichment method

These methods are proper for every thin coating except thermal spray coating. Thin layer coatings are successfully used in gas turbine industry, coating turbine and stator blades and combustion rooms. The thin ceramic coating can conduct by methods of Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and Chemical Formed Processes (CFP).

2.5. Finite Element Analysis (FEA)

Testing strength of the material or applied stress can be use two methods, laboratory testing (experimental method) and numerical method (FEM). On laboratory test or experimental method, specimen material and the testing device must be prepared. Universal Testing Machine (UTM) used to test the tensile strength and compressive stress of materials. The experimental method is used to validate of FEM result.

FEM (Finite Element Method) is another technique to test materials. features of FEM are structural analysis, heat transfer, fluid flow, etc. One of the advantages of FEM is known thermal stress based on temperature distribution. On this bachelor thesis use von-mises stress to analyze the stress distribution.

2.5.1. Von-mises stress

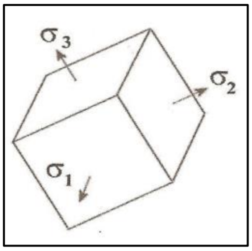


Figure 2. 14 Von-mises Stress

Von-mises stress is used to predict yielding of materials under complex loading from the results of uniaxial tensile stress. Von-mises is satisfactory for ductile material. The formula of von-mises can be seen in below:

$$\sigma vm = \sqrt{\frac{(\sigma 1 - \sigma 2)^2 + (\sigma 2 - \sigma 3)^2 + (\sigma 3 - \sigma 1)^2}{2}}$$

Equation 2. 5

Where:
σ_1: maximum principal stress
σ_2: middle principal stress
σ_3: minimum principal stress

2.6. Safety Factor

Safety factor or also known as Factor of Safety (FoS), used to provide design stress margin over material stress capacity (yield stress). There are two definitions for factor of safety:

1. The ratio of actual strength to actual applied load. Factor of safety can be calculated as:

   Factor of Safety = $\frac{Material\ Strength}{Working\ Stress}$

   Equation 2. 6

   Where:

- Material Strength (MPa)
- Working Stress (MPa)

2. Constant value issued by law or standard and shall exceed (design factor). Design stress of ductile material is 2/3 of yield stress value (ASME and API).

CHAPTER III
METHODOLOGY

This bachelor thesis conduct with simulations of exhaust valve system of 2-strokes diesel engine with 4 variations, which are: non-coated; nimonic 80A with 0.30 mm ceramic coated; nimonic 80A with 0.40 mm ceramic coated and nimonic 80A with 0.50 mm ceramic coated. The re-design process is conducted using 3D modeler and will analyze using Finite Element Method (FEM) for the thermal and mechanical load at 100% load and 100% rpm. The methodology of this bachelor thesis can be seen in Figure 3. 1 Research Flow Chart.

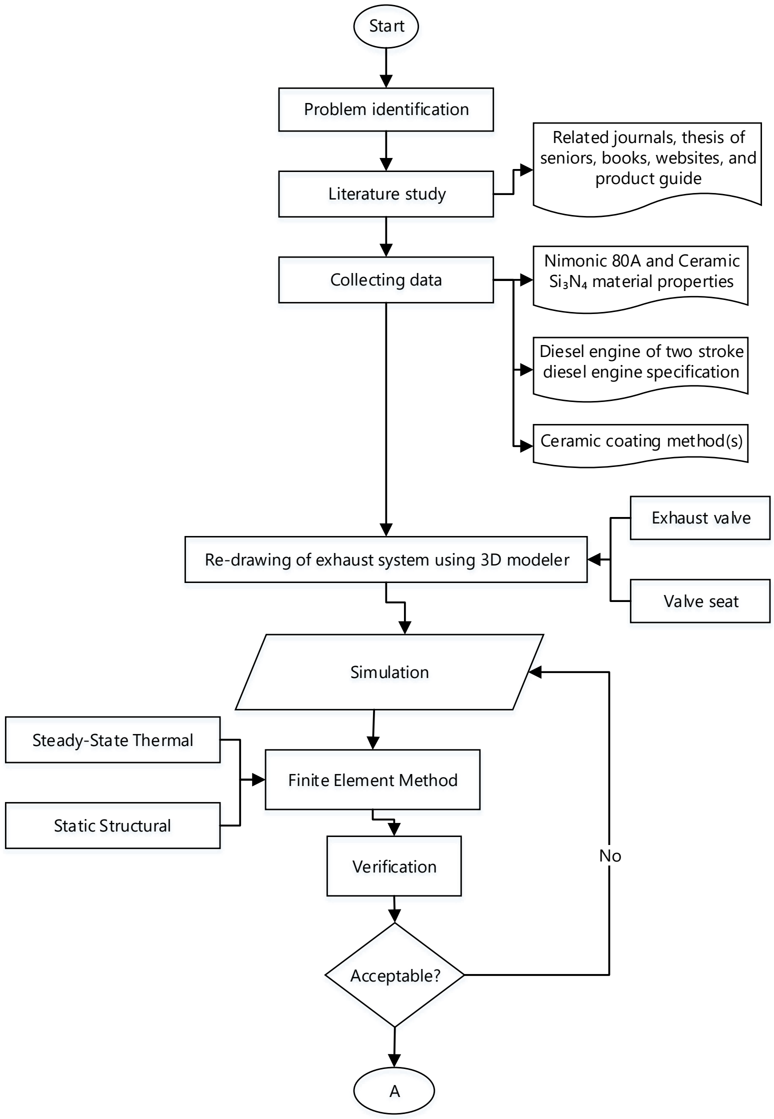


Figure 3. 1 Research Flow Chart

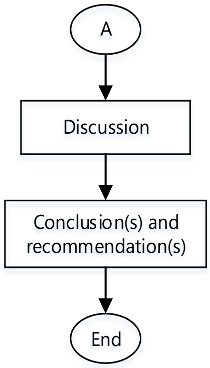


Figure 3. 1 Research Flow Chart (Continued)

Flowchart explanation:

3.1. Collecting Data

There are several required data to conduct this bachelor namely:

1. Diesel engine specification such as: 1. exhaust valve size & valve seat dimension (Figure 3. 2); 2. exhaust gas temperature & cylinder pressure at 100% load and 100% rpm obtained from project guide. The dimension of the exhaust valve and valve seat can be seen at Table 3. 1 and Table 3. 2. Exhaust gas temperature is 420°C and pressure inside the cylinder is 140 bar obtained from diesel engine project guide (Figure 2. 2).

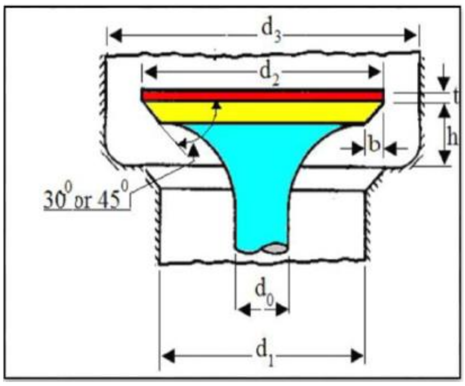


Figure 3. 2 Exhaust Valve and Valve Seat Dimension (Gawale & Shelke, 2016)

Table 3. 1 Exhaust Valve Dimension

Symbol	Design Parameter	Value
d2	combustion face diameter	181.52 mm
b	width of seating	17.4 mm
d0	diameter of valve stem	40.2 mm
α	Seating angle	30
l	Length of valve stem	526.54 mm
t	thickness of valve disc	3.55 mm

Table 3. 2 Valve Seat Dimension

Symbol	Design Parameter	Value
d1	Port Diameter	152.26 mm
d3	Valve Head Opening Diameter (Calculated)	236.92 mm
h	Valve Lift (Calculated)	43.95 mm

2. Nimonic 80A and Ceramic (Si_3N_4) material properties can be seen at Table 3. 3 and Table 3. 4. In finite element analysis for steady state thermal and static structural required some properties data of material, namely:
   - Density
   - Modulus Elasticity (Young Modulus)
   - Poison Ratio
   - Tensile Yield Strength
   - Tensile Ultimate Strength
   - Thermal Conductivity
   - Thermal Expansion Coefficient
   - Bulk Modulus
   - Shear Modulus

Table 3. 3 Nimonic 80A Material Properties

Properties	Value	Unit
Density	8190	kg/m^3
Coefficient of Thermal Expansion	1.27x10^-5	m/m^0C
Young Modulus	2.25x10^11	Pa
Poisson's Ratio	0.3	-
Bulk Modulus	1.875x10^11	Pa
Shear Modulus	8.654x10^10	Pa
Tensile Yield Strength	7.8x10^8	Pa
Tensile Ultimate Strength	1.25x10^9	Pa
Isotropic Thermal Conductivity	11.2	W/m^0C

Table 3. 4 Si_3N_4 Material Properties

Properties	Value	Unit
Density	3210	kg/m^3
Coefficient of Thermal Expansion	3.2x10^-6	m/m^0C
Young Modulus	3.05x10^11	Pa
Poison's Ratio	0.26	-
Bulk Modulus	2.12x10^11	Pa
Shear Modulus	1.21x10^11	Pa

Properties	Value	Unit
Tensile Ultimate Strength	7.5x10^8	Pa
Isotropic Thermal Conductivity	21	W/m^0C

3. Ceramic coating (thin) layer method for the exhaust valve. Since maximum coating thickness for diesel engine components is 0.5mm, so the variation of the coating are 0.3mm, 0.4mm, and 0.5mm.

Point number 1, 2, & 3 are used to determine the design parameter that will be used for stress analysis. Materials that will be used are Nimonic 80A as base material and ceramic (Si_3N_4) as a coating layer on combustion face.

3.2. Re-design of Exhaust System

Re-design of the exhaust system (exhaust valve and valve seat) with 3D design modeler regarding type and size of the two diesel engine sample. In the process of modeling, the size required are exhaust valve dimension, valve seat dimension, and coating thickness. On this step, the ceramic coating is also designed at combustion face with thickness variation: 0.3mm, 0.4mm, and 0.5mm.

1. Exhaust Valve

   According to Table 3. 1, the exhaust valve 3D form can be seen in Figure 3. 3.

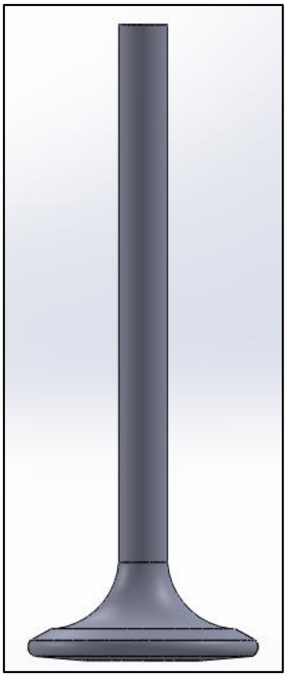


Figure 3. 3 Exhaust Valve 3D Form

2. Valve seat
   In order to achieve of exhaust valve stress as real condition, valve seat used as fixed supports. According to Table 3. 2, the valve seat of 2-strokes diesel engine can be seen in Figure 3. 4.

Figure 3. 4 Cross-Section of Valve Seat 3D Form

3.3. Verification

After conduct simulation using FEM, there are some steps for verified the simulation results to be fulfilled, namely:

1. Exhaust valve loads and supports for simulation
   Loads in exhaust valve which have a high contribution to caused stress are combustion pressure and exhaust gas temperature. Combustion pressure and gas temperature value are obtained from engine project guide performance curve with a value of 140 MPa and 420°C respectively. These are applied in combustion face of the exhaust valve.
   Supports are used to simulate structural stress because if there is no fixing support stress cannot be calculated by the software. Valve seat used as fixing support according to related journal (Witek, 2016). Fixed supports configuration can be seen in Figure 3. 5, where fixed support applied at the outer side of valve seat.

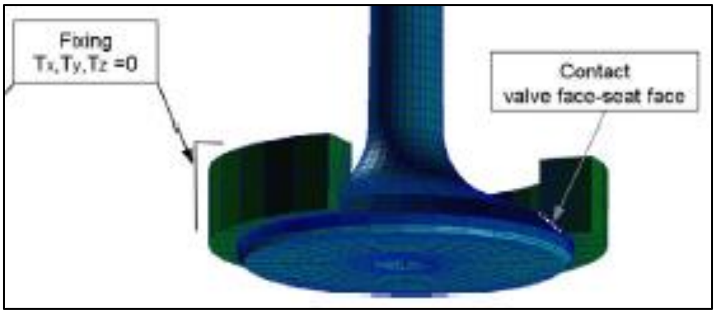


Figure 3. 5 Fixing Supports

2. Material properties
   In order to verify of material properties, simple model simulation is conducted. Simulation using 2 plates of Nimonic 80A and Ceramic material and loads are applied. Model dimension can be seen in Table 3. 5.

Table 3. 5 Simple Model Dimension

Model	H (mm)	B (mm)	L Nimonic (mm)	L Ceramic (mm)
Nimonic with 0.5mm Ceramic Coating	200	200	50	0.5

2.1. Temperature Distribution

Temperatures are given at the outer side of nimonic 80A and ceramic with a value of 250°C and 420°C respectively. The result can be seen in Figure 3. 6.

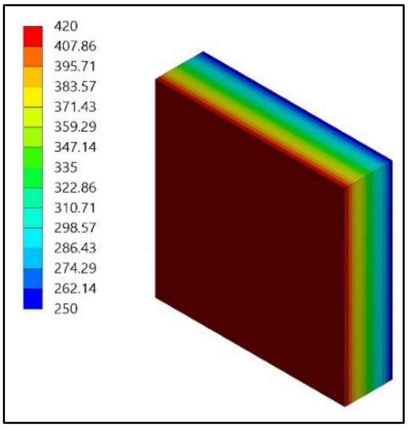


Figure 3. 6 Temperature Distribution

- Temperature at ceramic outer side is 420°C
- Temperature between ceramic and nimonic (T3) is 419.69°C
- Temperature at nimonic outer side is 250°C

Manual calculation is conduct to ensure material properties (thermal conductivity) works. From **Error! Reference source not found.**10 obtained:

- A : 40000mm^2
- L_N : 50mm
- L_c : 0.5mm
- k_N : 11.2 W/m°K
- k_C : 21 W/m°K

$$Q = (T1 - T2)/(Rcond, total)$$

Where:

Q : Heat (W)
T1 : Ceramic outside temperature: 420°C
T2 : Nimonic outside temperature: 250°C
$Rcond_{total}$: Total conductivity resistance ($\frac{L}{k.A}$)

Rcond calculation:

$R_{cond_{ceramic}}$	: $\frac{5x10^{-4}m}{21\ W/mK\ x\ 4x10^{-2}m} = \frac{1}{1680}K/W$
$R_{cond_{nimonic}}$	: $\frac{5x10^{-3}m}{11.2\ W/mK\ x\ 4x10^{-2}m} = \frac{25}{224}K/W$
$R_{con,\ total}$	: $R_{cond_{ceramic}} + R_{cond_{nimonic}} = \frac{377}{3360}K/W$
Q_{total}	: $\frac{693.15K-523.15K}{\frac{377}{3360}K/W}$ = 1515.119363 W
$Q_{ceramic}$	: $\frac{k.A.\Delta T}{L} = \frac{21W/mK.4x10^{-2}m^2.(693.15K-T1)}{5x10^{-4}m}$
1515.119 W	: $\frac{21W/mK.4x10^{-2}m^2.(693.15K-T1)}{5x10^{-4}m}$
T3	: 419.098°C

2.2. Thermal stress

Static-structural conduct to simulate thermal stress caused by temperature change. Simulation is conducted with boundary condition (Figure 3. 7) of:

- Fixing support at the outer side of nimonic and ceramic.
- Different temperature from the initial condition is 15°C (ΔT).

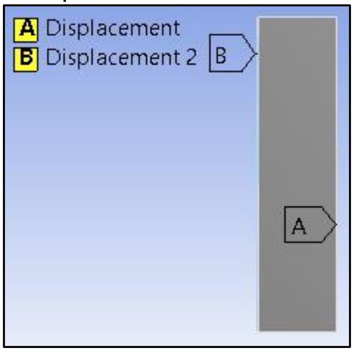


Figure 3. 7 Boundary Condition

Thermal stress result can be seen in Figure 3. 8, the highest von-mises stress is 43.722 MPa and the lowest is 42.558 MPa.

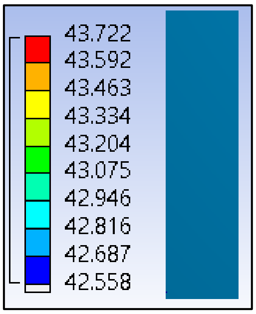


Figure 3. 8 Thermal Stress Distribution

Manual calculation is conduct to ensure mechanical properties of nimonic and ceramic are proper. To calculate thermal stress some mechanical properties are required, namely:

1. Young's Modulus (E)
   $E_{Nimonic}$: 2.25 x 10^{11} Pa
   $E_{Ceramic}$: 3.05 x 10^{11} Pa
2. Thermal expansion coefficient (α)
   $\alpha_{Nimonic}$: 12.7 x 10^{-6}/°C
   $\alpha_{Ceramic}$: 3.2 x 10^{-6}/°C
   Thermal deformation:
   δ_T = α.ΔT.L
   $\delta_{Tnimonic}$ = 12.7 x 10^{-6}/^{0}C x 15°C x 5 x 10^{-2}m
   = 9.525 x 10^{-6}m
   $\delta_{Tceramic}$ = 3.2 x 10^{-6}/^{0}C x 15°C x 5 x 10^{-3}m
   = 2.4 x 10^{-7}m

   Thermal stress:
   $\delta_C+\delta_N$ = $\delta_{Tn} + \delta_{Tc}$
   $(PxL/AxE)_c+(PxL/AxE)_N$ = 9.548x10^{-6}m
   $$\left(\frac{Px0.5mm}{4x10^4mm^2x3.05x10^{11}Pa}\right)+\left(\frac{Px50mm}{4x10^4mm^2x2.25x10^{11}Pa}\right)=9.548x10^{-3}mm$$

   $$\left(\frac{0.5P}{1.22x10^{16}mmPa}\right)+\left(\frac{50P}{9x10^{15}mmPa}\right)=9.548x10^{-3}mm$$

   $$\frac{4.5x10^{15}P+6.1x10^{17}P}{1.098x10^{32}mmPa}=9.548x10^{-3}mm$$

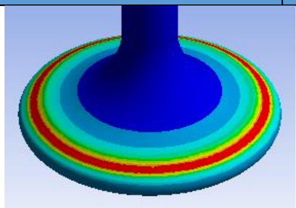
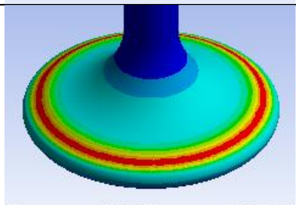
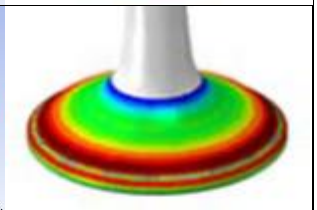
   $$\frac{6.145x10^{17}\,P}{1.098x10^{32}mmPa}=9.548x10^{-3}mm$$

   P = 1.706x10^{12}mm^{2}Pa
   $$\sigma=\frac{P}{A}$$
   Because A_N=A_C, so
   $$\sigma=\frac{P}{A}=\frac{1.706x10^{12}mm^2\text{Pa}}{4x10^4mm^2}=42650000\,Pa=42.65\text{ MPa}$$

3. Location of stress occurs
   After testing the material properties, it can be continued to simulate the real model which is exhaust valve and valve seat. After the simulation, the author compared the results with

existing journal concerning on stress location are occur on exhaust valve (Kum-Chul, Sang-Woo Cha, & Ji-Ho Kim, 2014). Types of the simulation are thermal stress and structural stress. Comparison result can be seen in Table 3. 6, it can be seen the stress that caused by thermal distribution is located at seat face and stress caused by thermo-mechanical is also located on seat face area. Since results from simulation and existing journal are similar (in the location of stress are occurs), research can be continued.

Table 3. 6 Location the Stress Occur

Stress	Simulation	Existing Journal
Thermal load		
Thermal load + Combustion Pressure		

3.4. Software Simulation

Simulation is conducted using Finite Element Method (FEM). FEM is used for analyze the design and simulate the operation condition of a diesel engine (temperature and pressure). After all required data has been obtained, here are steps or stages of the simulation using FEM:

1. Input Engineering Data

	A	B	C
1	Property	Value	Unit
2	Density	7850	kg m^-3
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	1.2E-05	C^-1
5	Reference Temperature	22	C
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisson's Ratio	
8	Young's Modulus	2E+11	Pa
9	Poisson's Ratio	0.3	
10	Bulk Modulus	1.6667E+11	Pa
11	Shear Modulus	7.6923E+10	Pa
12	Field Variables		
13	Temperature	Yes	
14	Shear Angle	No	
15	Degradation Factor	No	
16	Alternating Stress Mean Stress	Tabular	
20	Strain-Life Parameters		
28	Tensile Yield Strength	2.5E+08	Pa
29	Compressive Yield Strength	2.5E+08	Pa
30	Tensile Ultimate Strength	4.6E+08	Pa
31	Compressive Ultimate Strength	0	Pa
32	Isotropic Thermal Conductivity	60.5	W m^-1 C^-1

Figure 3. 9 Engineering Data Input

Engineering data input is the process of input the material properties of nimonic 80A and Si_3N_4 to the software material properties database (Figure 3. 9). The required material properties data as follows:

- Density
- Modulus Elasticity (Young Modulus)
- Poison Ratio
- Tensile Yield Strength
- Tensile Ultimate Strength
- Thermal Conductivity
- Thermal Expansion Coefficient

2. Meshing

After inputting data of material properties, simulation cannot conduct before meshing process is done. Meshing process is dividing geometry of model into elements and nodes. The quantity of node or element are affected results of the simulation, more of nodes or elements/meshing will give a better result. An example of meshing result of exhaust valve can be seen in Figure 3. 10. Meshing configuration on this bachelor thesis is:

- Use advance size function : Curvature
- Relevance center : Fine
- Initial size seed : Active Assembly
- Smoothing : High
- Transition : Slow
- Span angle center : Fine

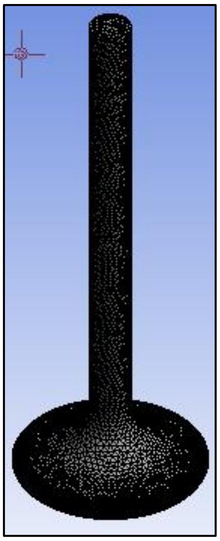


Figure 3. 10 Exhaust Valve Mesh

There are some indicators to indicate the mesh result is good or not, which are: aspect ratio and skewness. Aspect ratio is a comparison between the longest side and shortest side from the element. Best value of aspect ratio is an approach to 1. Skewness is the other indicators of mesh quality, quality of mesh depend on skewness value can be seen in Table 3. 7.

Table 3. 7 Skewness Value

Value of Skewness	Cell Quality
1	degenerate
0.9-1	bad (silver)
0.75-0.9	poor
0.5-0.75	fair
0.25-0.5	good
>0-0.25	excellent
0	equilateral

After meshing process and optimization of mesh from the geometry then the results can be seen in Table 3. 8. Skewness factor (average) of all 4 samples are below of 0.25 which indicated the mesh is excellent.

Table 3. 8 Meshing Results

Indicator	Non-Coating	0.3mm	0.4mm	0.5mm
Nodes	526230	529629	527610	526222
Elements	355929	358637	357169	355909
Skewness	0.24505	0.24785	0.24539	0.24508

3. Surface Contact

There are 2 surface contacts on this simulation. First surface contact is defined at the adjacent surface between the valve seat and seat face. Frictional type was used with 0.05 frictional coefficient, it is based on the existing journal (Witek, 2016). The second surface contact is between ceramic (coating) and nimonic 80A (exhaust valve) material. Since ceramic material is used as a coating, bonded contact type is used. These two surface contacts are used in each simulation (load case) of each coating thickness variation.

4. Boundary Condition

The boundary condition is environment condition or it can be as load(s) and support(s) on the geometry. Loads in exhaust valve diesel engine are temperature of exhaust gas, pressure from inside the cylinder, and fixed support on valve seat (Figure 3. 11).

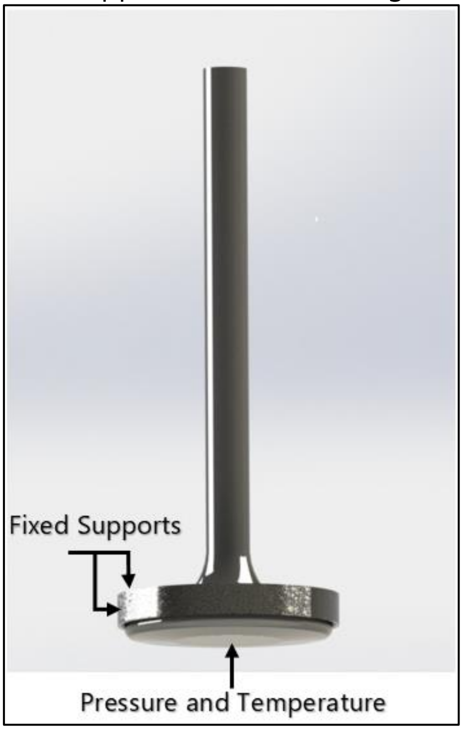


Figure 3. 11 Exhaust Valve Load

Loads are given in steady-state condition, where there is no change in load with respect to time. There are two analysis systems used in this simulation (steady-state thermal and static structural) and divided into 3 different load cases, namely: 1. Thermal stress; 2. Mechanical stress; 3. Thermo-mechanical stress. The configuration of analysis system for each load case are:

4.1. Thermal Stress (1st load)

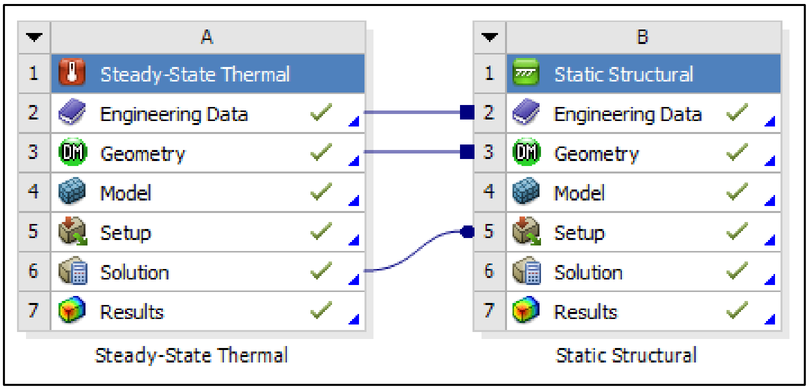


Figure 3. 12 Thermal Stress Schematic

There are 2 parts (analysis systems) on thermal stress analysis, which are steady-state thermal and static structural. Steady-state thermal is used to apply thermal loads: exhaust gas temperature and valve seat temperature. Exhaust gas temperature that applied is 420°C at combustion face, it is based on engine performance curves data. The second load is temperature of 250°C on the valve seat. Loads of steady state thermal is presents in **Error! Reference source not found.**Figure 3. 13 and Figure 3. 14.

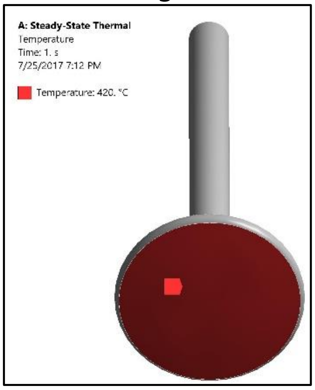


Figure 3. 13 Exhaust Gas Temperature Input

Other required conditions for steady-state thermal simulation are initial condition and coupling between the adjacent surface (for coated exhaust valve). The initial condition is to determine initial temperature of simulation, the author used 50°C as an initial condition. The determination is based on minimum engine jacket cooling water temperature before can be engine started. Coupling is used to give better temperature distribution. Since exhaust valve and coated material are bonded, so there is no temperature difference between those two surfaces. Coupling is given between ceramic coating and exhaust valve combustion face.

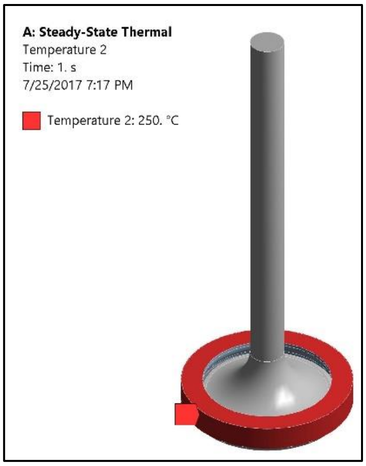


Figure 3. 14 Valve Seat Temperature Input

4.2. Mechanical Stress (2nd load)

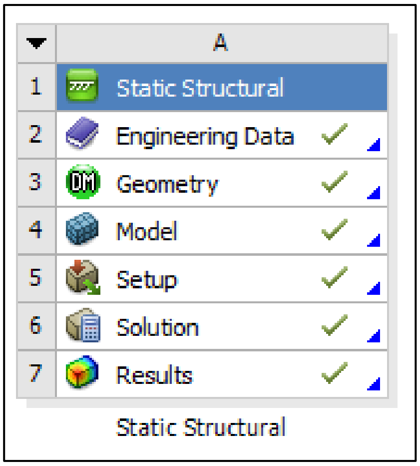
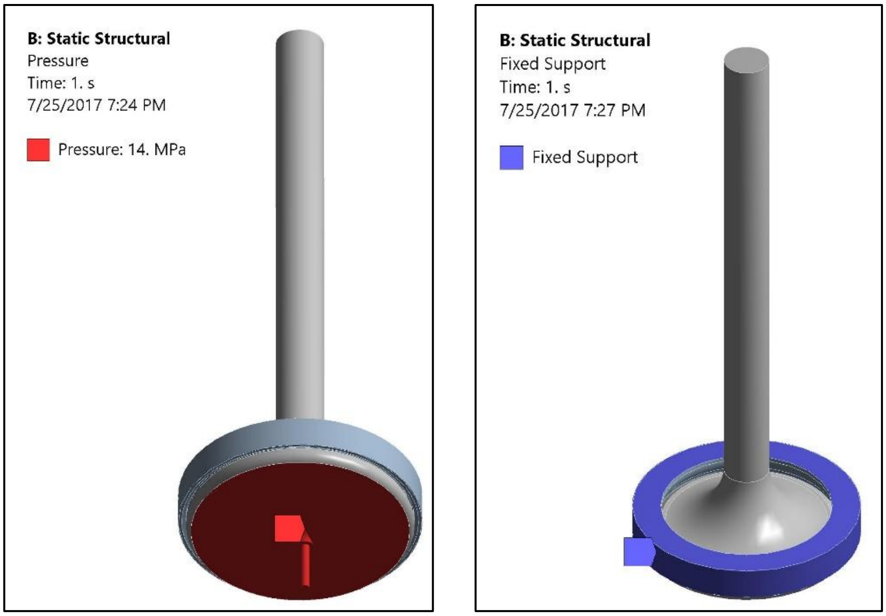


Figure 3. 15 Structural Stress Schematic

Static structural is used to simulate structural stress caused by cylinder pressure. On static-structural there are 2 loads, which are pressure and fixed supports. Pressure is given on combustion face of 140 bars (14 MPa) on the red color, its accordance to diesel engine project guide. Fixed supports is applied on seat face area (blue colored), it is given to simulate the function of the engine case. Pressure and fixed supports are given can be seen in Figure 3. 16 (a) and (b).



(a) *(b)*

Figure 3. 16 (a) Pressure Input and (b) Fixed Supports

4.3. Thermo-Mechanical Stress (3rd load case)

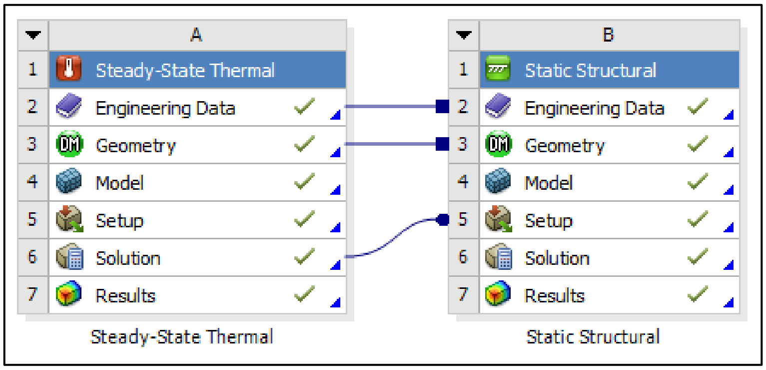


Figure 3. 17 Thermo-Mechanical Stress Schematic

Thermo-mechanical stress simulation is a combination between steady-state thermal and static structural. Similar to 1st load case, the temperature of exhaust gas, valve seat temperature, and initial condition are inputted. Next, solution of steady-state thermal is connected to static structural setup, it is intended to import thermal load from the steady-state thermal simulation. Fixed support at valve seat and pressure at combustion face are also input as same as the 2nd load.

3.5. Discussion

On this stage after comparing the simulation results with the previous journal, the author will discuss the simulation results. The topics of discussion are stress (von-mises) distribution of each load case (1^{st}, 2^{nd}, and 3^{rd}) and temperature distribution of those 4 models.

3.6. Conclusions and Recommendations

The final step is to make conclusions from this bachelor thesis to provide an answer from the existing problems and recommendation(s) for next research consist of the possible topic(s) for next bachelor thesis and minus from this bachelor thesis.

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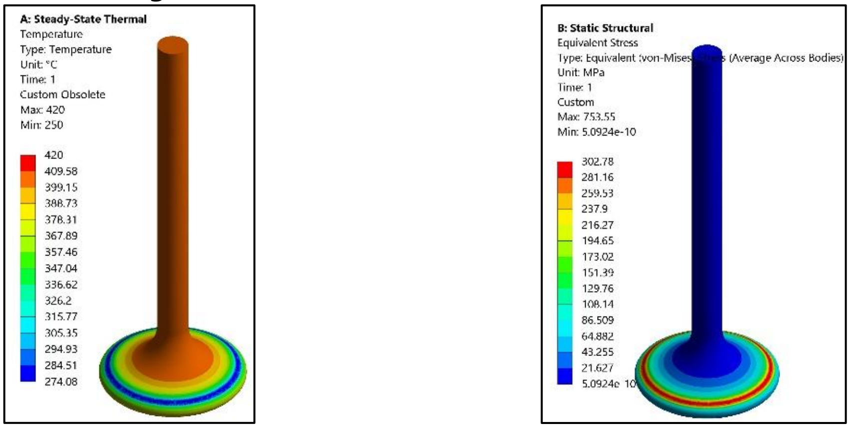
CHAPTER IV SIMULATION RESULT & DATA ANALYSIS

On this chapter will discuss simulation results and analyze the results. Simulation results will be divided according to coating thickness. Simulation results present of temperature distribution, thermal stress, mechanical stress and thermo-mechanical stress.

4.1 Simulation Result

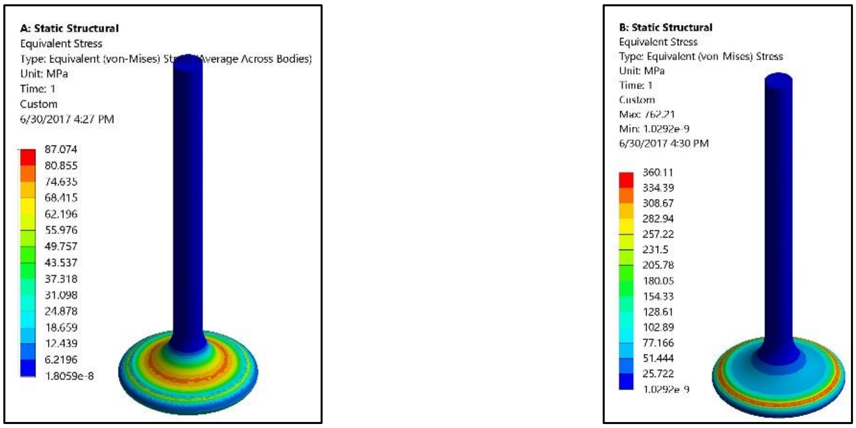
4.1.1 Non-Coating



(a) *(b)*

Figure 4. 1 Non-Coated (a) Temperature Distribution and (b) Thermal Stress

Figure 4. 1 (a) shows temperature distribution on the non-coated exhaust valve. The highest temperature occurs at combustion face with a value of 420°C and the lowest temperature occurs at valve seat area with a value of 274.08°C. According to Figure 4. 1 (b) the highest thermal stress occurs at valve seat area with a value of 302.78 MPa and the lowest is 5.092×10^{-10} MPa on the valve stem.



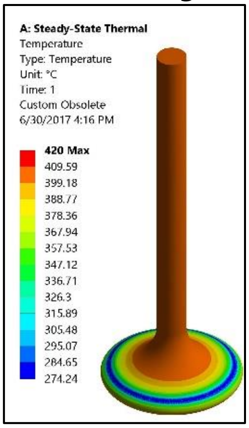
(a) *(b)*

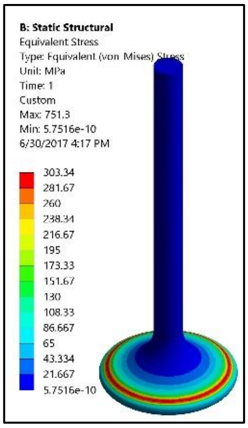
Figure 4. 2 Non-Coated (a) Mechanical Stress and (b) Thermo-mechanical Stress

Figure 4. 2 (a) present von-mises stress caused by combustion pressure (mechanical load) by 14 MPa. The highest stress located at seat face area with a

value of 87.074 MPa. Another stress occurs at fillet area with a range of 67.724 MPa to 77.399 MPa. Figure 4. 2 (b) shows stress caused by the combination of the mechanical and thermal load. The highest stress occurs at seat face area with a value of 360.11 MPa.

4.1.2 0.3mm Coating

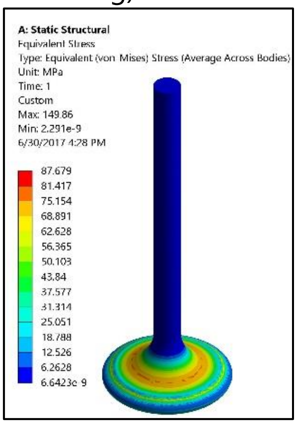


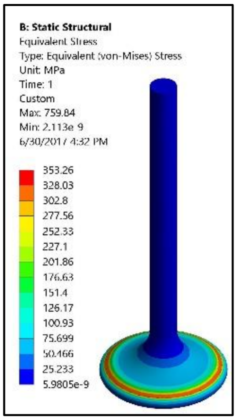


(a) *(b)*

Figure 4. 3 0.3mm Coated (a) Temperature Distribution and (b) Thermal Stress

Figure 4. 3 (a) show temperature distribution on exhaust valve with a 0.3mm ceramic coated, it can be seen that the highest temperature occur at combustion face with a value of 420°C and lowest temperature located at seat face area with a value of 274.24°C. Meanwhile, at Nimonic 80A combustion face the temperature is 419.52°C. On Figure 4. 3 (b) show thermal stress due to exhaust gas temperature on the exhaust valve with the highest stress located at seat face with a value of 303.34 MPa. Meanwhile, thermal stress on combustion face (ceramic coating) is 38.426 MPa.



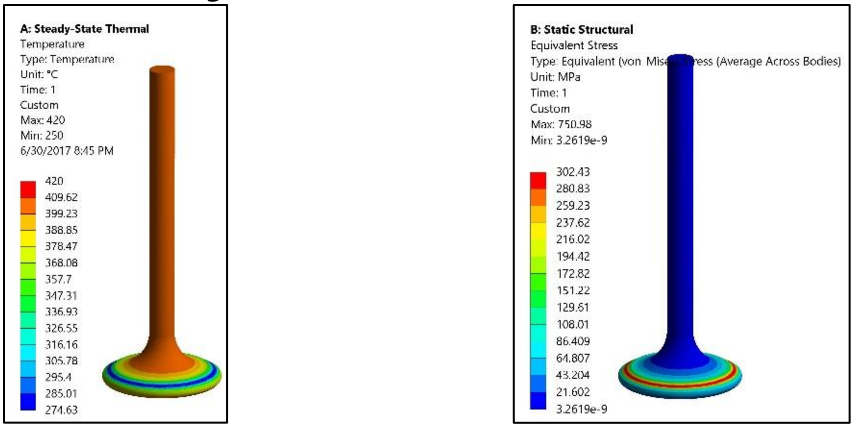


(a) *(b)*

Figure 4. 4 0.3mm Coated (a) Mechanical Stress and (b) Thermo-mechanical Stress

Figure 4. 4 (a) show von-mises stress caused by combustion pressure on exhaust valve with coating thickness of 0.3mm. The highest stress occurs at the seat face (contact area between the exhaust valve and valve seat) with a value of 87.679 MPa, meanwhile at ceramic coating is 82.051 MPa. On Figure 4. 4 (b) show thermo-mechanical stress on exhaust valve with 0.3mm ceramic coating. The highest stress occurs on seat face with a value of 353.26 MPa, meanwhile on the ceramic coating is 120.69 MPa.

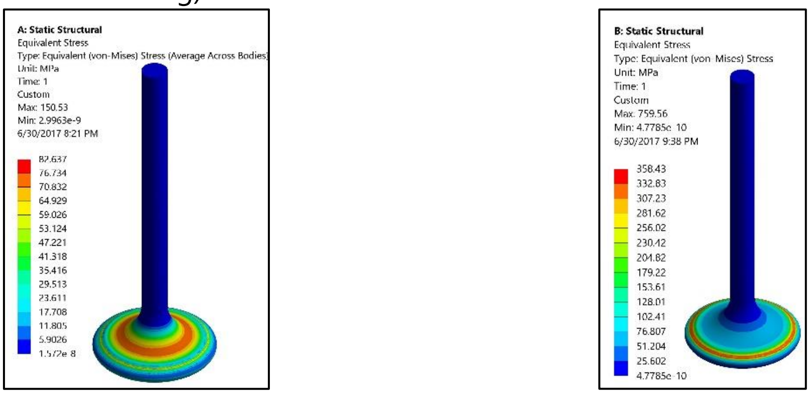
4.1.3 0.4mm Coating



(a) *(b)*

Figure 4. 5 0.4mm Coated (a) Temperature Distribution and (b) Thermal Stress

Figure 4. 5 (a) shows temperature distribution of exhaust valve with 0.4mm ceramic coating. The highest temperature occurs at combustion face and the lowest temperature occurs at seat face area with a value of 420°C and 274.63°C respectively. Figure 4. 5 (b) show thermal stress distribution. The highest thermal stress occurs at seat face with 302.43 MPa and 37.07 MPa at combustion face (ceramic coating).

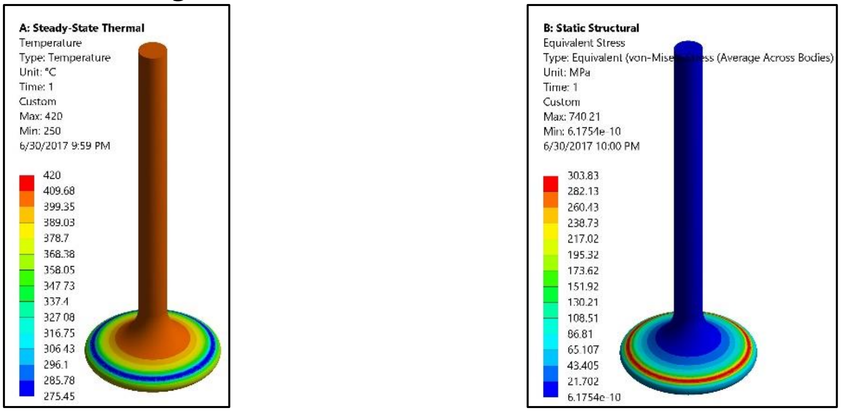


(a) *(b)*

Figure 4. 6 0.4mm Coated (a) Mechanical Stress and (b) Thermo-mechanical Stress

Figure 4. 6 (a) shows the mechanical stress of exhaust valve with the 0.4mm ceramic coating. Valve seat area has higher stress than another area with a value of 82.637 MPa, meanwhile at ceramic coating is 80.153 MPa. Figure 4. 6 (b) show the thermo-mechanical stress of exhaust valve with a 0.4mm ceramic coating, the highest stress value occurs at seat face with a value of 358.43 MPa, meanwhile at combustion face (ceramic coat) is 118.58 MPa.

4.1.4 0.5mm Coating



(a) (b)

Figure 4. 7 0.5mm Coated (a) temperature Distribution and (b) Thermal Stress

Figure 4. 7 (a) shows temperature distribution of exhaust valve with coating thickness of 0.5mm. The highest temperature located at combustion face, where this area directly contacts with combustion chamber with a value of 420°C and the lowest temperature located at seat face with a value of 275.45°C. Figure 4. 7 (b) show thermal stress caused by exhaust gas temperature, where the highest stress occurs at seat face area with 303.83 MPa, meanwhile at combustion face (ceramic coating) is 35.562 MPa.

(a) (b)

Figure 4. 8 0.5mm Coated (a) Mechanical Stress and (b) Thermo-mechanical Stress

Figure 4. 8 (a) show mechanical stress caused by combustion pressure on the cylinder. The highest stress occurs at the seat face with a value of 84.635 MPa. On Figure 4. 8 (b) show the thermo-mechanical stress of exhaust valve with coating thickness of 0.5mm. The highest stress occurs at seat face area with a value of 364.07 MPa and 117.32 MPa at combustion face (ceramic coating).

4.2 Data Analysis

After conduct the simulation and get the results (thermal stress, mechanical stress, and thermo-mechanical stress), it will be discussed based on temperature distribution, mechanical stress, thermal stress, thermo-mechanical stress, and the safety factor of each exhaust valve.

4.2.1 Temperature Distribution

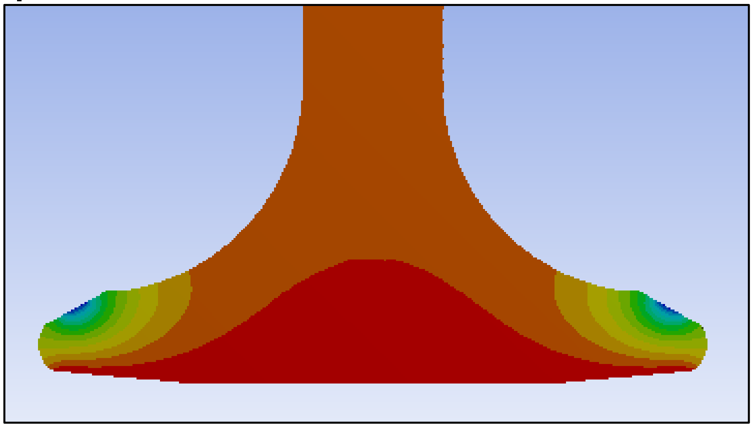


Figure 4. 9 Temperature Distribution of Exhaust Valve

Figure 4. 9 show temperature distribution on the exhaust valve. It can be seen there is temperature differences especially on valve head area. Seat face area has a lower temperature than another area, it is because seat face area contacted with cooled parts (valve seat).

Table 4. 1 Temperature Distribution at Valve Seat Area

Exhaust Valve	Temperature (^{0}C)
Non-Coating	274.08
0.3mm Coating	274.24
0.4mm Coating	274.63
0.5mm Coating	275.45

The temperature distribution of exhaust valve that obtained from the simulation can be seen in Table 4. 1. It showed the different temperature on each exhaust valve at seat face area. There is an increase of temperature at seat face area in each variation. The differences in temperature is due to the ceramic material has higher thermal conductivity coefficient than nimonic 80A material.

From Figure 4. 10 show temperature differences of 4 samples, the thicker coating will have a higher temperature at seat face area. Thermal conductivity coefficient of Nimonic 80A and Si_3N_4 are:

- Nimonic 80A : 11.2 W/m^0C
- Ceramic (Si_3N_4) : 21 W/m^0C

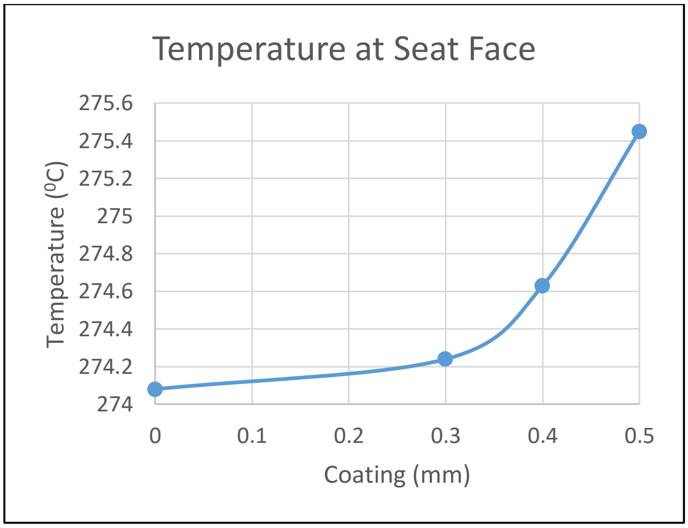


Figure 4. 10 Graphic of Temperature Differences at Seat Face

4.2.2 Structural Stress

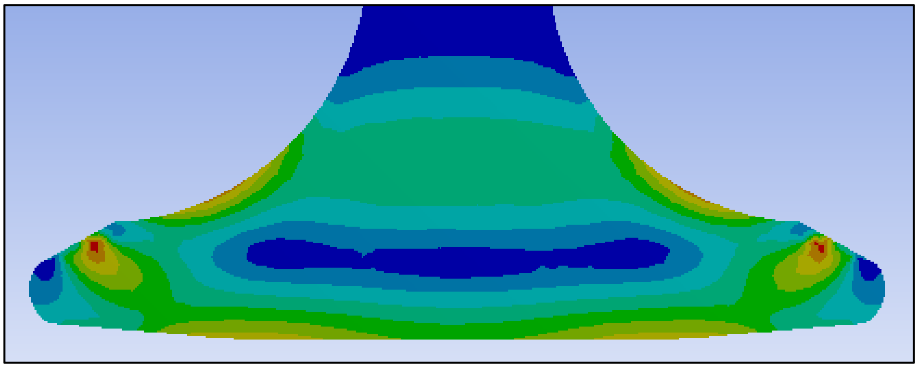


Figure 4. 11 Mechanical Stress Distribution of Non-Coated Exhaust Valve

Figure 4. 11 shows von-mises stress distribution of non-coated exhaust valve caused by compression from inside the cylinder. The highest stress occurs at seat face area, it because there is valve seat as a fixing supports. Another stress occurs at combustion face and fillet area. Stress on seat face can be seen in Table 4. 2. It can be seen, the effect of ceramic coating will reduce the mechanical stress on seat face area. Exhaust valve with 0.4mm coating thickness has the lowest mechanical stress with a value of 82.637 MPa.

Table 4. 2 Structural Stress on Si3N4

Coating	Von-misses Stress (MPa)
0.3mm	82.051
0.4mm	80.153
0.5mm	78.052

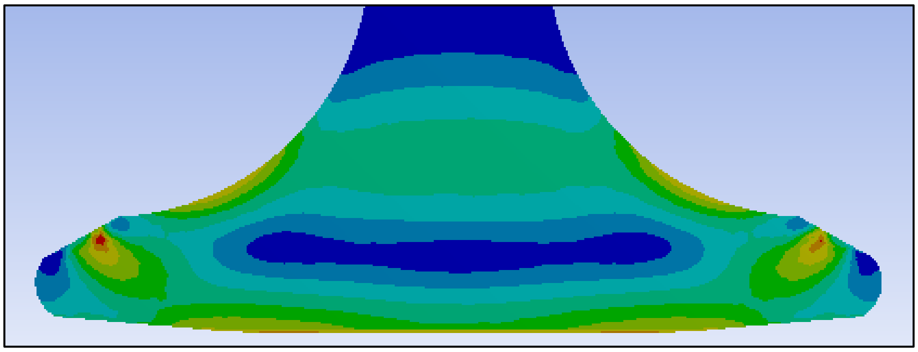


Figure 4. 12 Mechanical Stress Distribution of Coated Exhaust Valve

Figure 4. 12 shows von-mises stress distribution on coated exhaust valve. Stress occurs in the same location with the non-coating exhaust valve. The highest stress due to compression load occurs at seat face area and combustion face. Tensile stress occurs at fillet area same as a non-coating exhaust valve. Stress on ceramic coating can be seen in Table 4. 3. All mechanical stress simulation results can be seen in **Error! Reference source not found.**.

Table 4. 3 Structural Stress on Nimonic 80A (Seat Face)

Coating	Von-misses Stress (MPa)
Non-Coating	87.074
0.3mm Coating	87.679
0.4mm Coating	82.637
0.5mm Coating	84.635

4.2.3 Thermal Stress

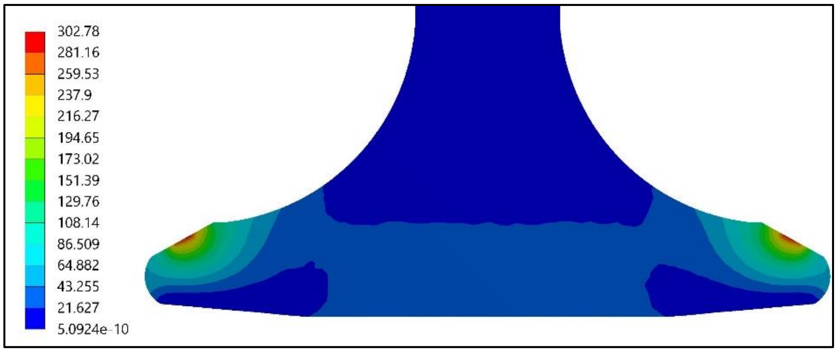


Figure 4. 13 Thermal Stress Distribution of Non-Coated Exhaust Valve

Figure 4. 13 shows thermal stress distribution on the non-coated exhaust valve. The highest stress occurs at seat face area which contacts with the valve

seat. Since outside of valve seat are given fixed supports, then valve seat only can expand to exhaust valve caused by thermal expansion. The exhaust valve is also expanded due to temperature change, resulting in compression on seat face area which caused by expansion of valve seat and exhaust valve its self. Thermal stress on exhaust valve can be seen in Table 4. 4. It can be seen that there is a addition of thermal stress due to increasing the coating thickness on combustion face.

Table 4. 4 Thermal Stress On Nimonic 80A (Seat Face)

Stress (Von-mises) on Nimonic 80A (MPa)				
Stress	Non-Coating	0.3mm Coating	0.4mm Coating	0.5mm Coating
Thermal	302.78	303.34	302.43	303.83

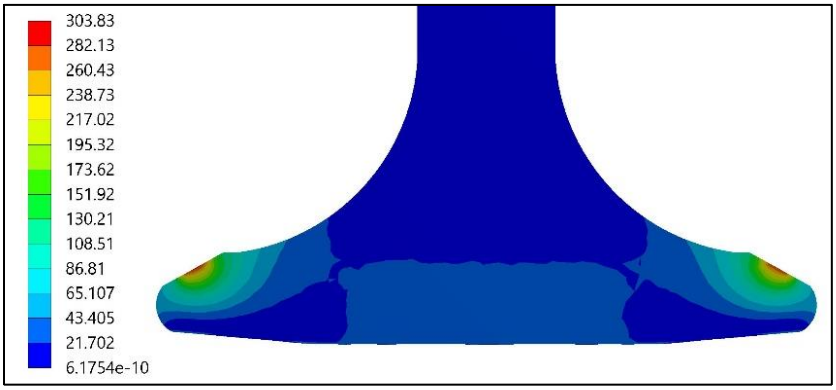


Figure 4. 14 Thermal Stress Distribution of Coated Exhaust Valve

Figure 4. 14 shows thermal stress distribution on exhaust valve with ceramic coated. Thermal stress distributed at valve head and the highest stress located at seat face area. The value of thermal stress at ceramic coating can be seen in Table 4. 5.

Table 4. 5 Thermal Stress on Si3n4

Stress (Von-mises) on Si3N4 (MPa)			
Stress	0.3mm Coating	0.4mm Coating	0.5mm Coating
Thermal	38.426	37.07	35.562

From Table 4. 4 and Table 4. 5 it can be inferred that the stress on nimonic 80A material is relatively increased, while the stress on ceramic coating is decreased along with the increase of coating thickness.

4.2.4 Thermo-Mechanical Stress

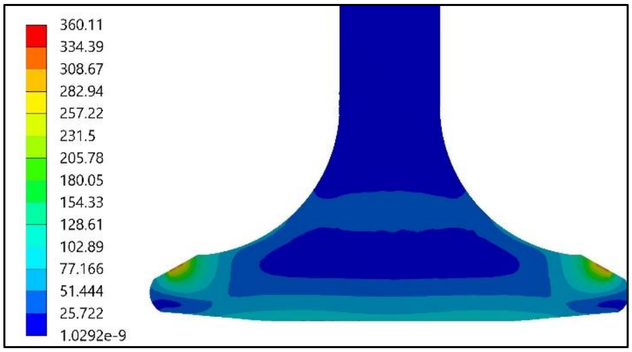


Figure 4. 15 Thermo-mechanical Stress Distribution of Non-Coated Exhaust Valve

Figure 4. 15 show equivalent (von-mises) stress on non-coated exhaust valve due to thermo-mechanical load. The highest stress occurs at seat face area with a value of 360.11 MPa. All stress occurs at valve head area since there is no tensile load from valve spring. Thermo-mechanical stress on Nimonic 80A seat face results can be seen in Table 4. 6. The stress are fluctuates, but it seems stress is increased due to increasing ceramic coating thickness.

Table 4. 6 Thermo-mechanical Stress on Nimonic 80A (Seat Face)

Stress (Von-mises) on Nimonic 80A (MPa)				
Stress	Non-Coating	0.3mm Coating	0.4mm Coating	0.5mm Coating
Thermo-Mechanical	360.11	353.26	358.43	364.07

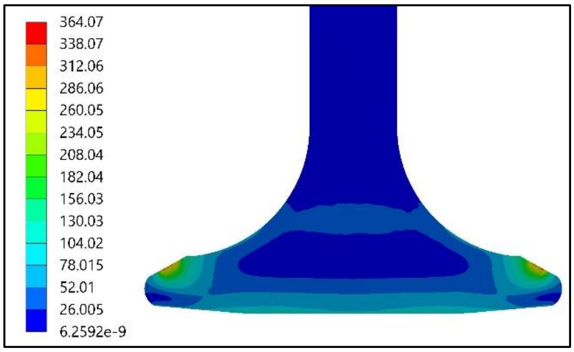


Figure 4. 16 Thermo-Mechanical Stress Distribution of Coated Exhaust Valve

Figure 4. 16 show equivalent (von-mises) stress on exhaust valve with ceramic coated due to thermo-mechanical load on the exhaust valve. The highest stress occurs at seat face area similar with a non-coated exhaust valve. Thermo-mechanical stress results on ceramic coat can be seen in Table 4. 7. The stress is decreased alongside with the increase of coating thickness.

Table 4. 7 Thermo-Mechanical Stress on Si3N4

Stress (Von-mises) on Si3N4 (MPa)			
Stress	0.3mm Coating	0.4mm Coating	0.5mm Coating
Thermo-Mechanical	120.69	118.58	117.32

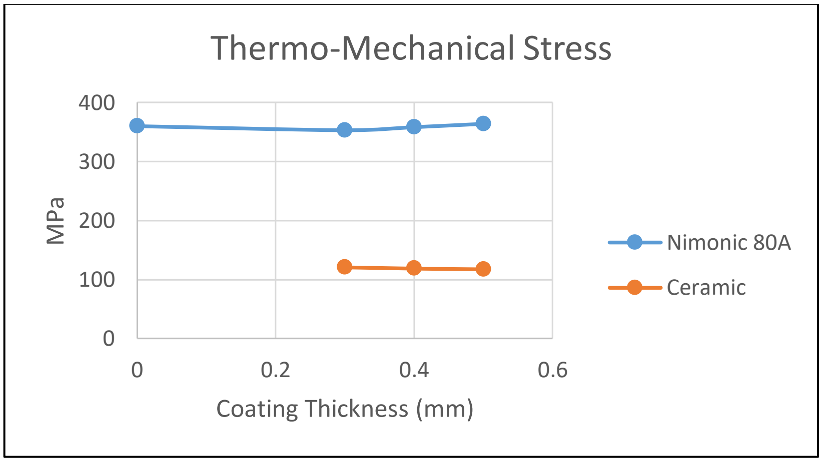


Figure 4. 17 Graphic of Thermo-mechanical Stress Differences

4.2.5 Safety Factor

According to Equation 2. 6, safety factors of exhaust valve can be calculated. Thermo-mechanical stress is used to calculate the safety factor. An example of calculation can be seen below and results can be seen in **Error! Reference source not found.**21.

1. FoS of Nimonic 80A:

   FoS $= \frac{Yield\ Strength}{Working\ Stress}$

   Since yield strength of Nimonic 80A is 780 MPa, for FoS of Nimonic 80A is:

   FoS = 780 MPa/360.11 MPa

   = 2.17

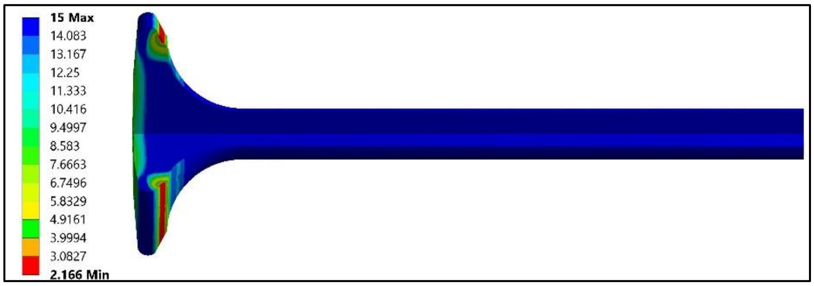


Figure 4. 18 Safety Factor Distribution of Exhaust Valve

Safety factor distribution of non-coated exhaust valve can be seen in Figure 4. 18, seat face area has the lowest safety factor since the highest stress occurs at that area with a value of 2.17. It is indicated exhaust valve failure can occur in that area as Figure 2. 7 showed.

2. FoS of Si_3N_4

   FoS $= \frac{Ultimate\ Strength}{Working\ Stress}$

   Since the ultimate strength of Si_3N_4 is 750 MPa, FoS of Si_3N_4 on 0.5mm ceramic coating is:

   FoS = 750 MPa/117.32 MPa

   = 6.39

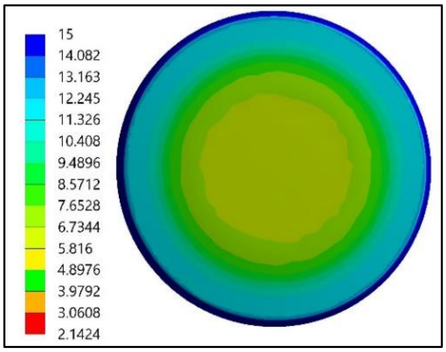


Figure 4. 19 Safety Factor Distribution of Ceramic Coat

Safety factor distribution of 0.5mm ceramic coat exhaust valve can be seen in Figure 4. 19. From Table 4. 8 it can be inferred that the safety factor of ceramic coat varies from 6.21 to 6.39. The lowest safety factor located at the center of combustion face where the highest stress occurs.

Table 4. 8 Safety Factor Results

Factor of Safety				
Material/Coating	Non-Coating	0.3mm Coating	0.4mm Coating	0.5mm Coating
Nimonic 80A	2.17	2.21	2.18	2.14
Si3N4	-	6.21	6.32	6.39

CHAPTER V CONCLUSION AND RECOMMENDATION

On this chapter will analyze results from the thermo-mechanical simulation. Von-mises stress used to analyze the results. The following is an analysis based on problem statement that has been discussed.

5.1. Stress Distribution of Non-Coated Exhaust Valve

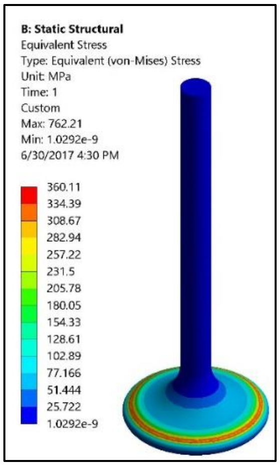


Figure 5. 1 Non-Coated Exhaust Valve Von-mises Stress Distribution

Figure 5. 1 show equivalent (von-mises) stress on the non-coated exhaust valve. The highest stress occurs at seat face area with a value of 360.11 MPa and the lowest is 1.0292×10^{-9} MPa located at the valve stem. High stress mostly occurs at valve head area since there is no tensile load from valve spring.

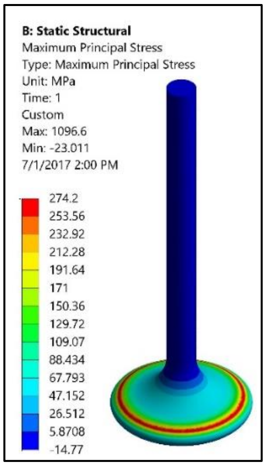


Figure 5. 2 Non-Coated Exhaust Valve Maximum Principal Stress Distribution

From Figure 5. 2 it can be seen of maximum principal stress due to thermo-mechanical load in non-coated exhaust valve. There is compression stress with a value of 14.77 MPa located on combustion face of the exhaust valve, this is due to compressive load from cylinder pressure.

5.2. Stress Distribution of Nimonic 80A with Ceramic Coating

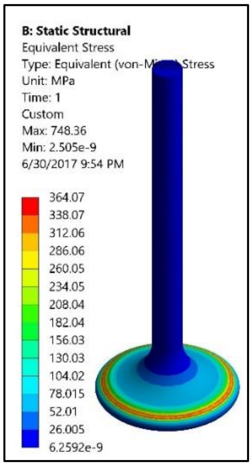


Figure 5. 3 Coated Exhaust Valve Von-mises Distribution

Figure 5. 3 show von-mises stress distribution on exhaust valve with 0.5mm ceramic coated. Stress distribution of exhaust valves with a ceramic coating is similar to the non-coated exhaust valve, the highest stress occurs at seat face area. Meanwhile, stress on ceramic coating is 120.69 MPa. Von-mises stress of exhaust valve with ceramic coating can be seen in Table 4. 6.

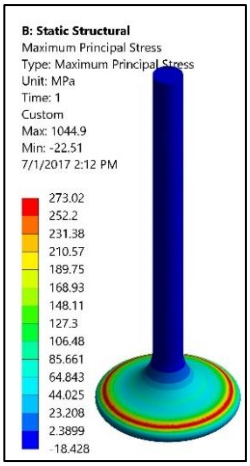


Figure 5. 4 Coated Exhaust Valve Maximum Principal Stress Distribution

Figure 5. 4 shows maximum principal stress distribution on exhaust valve with exhaust valve with 0.5mm ceramic coated. Maximum principal stress distribution of all variant coating thickness are similar, the highest stress located at seat face area and the lowest stress (compression) located at the ceramic coating.

5.3. Effect of Ceramic Coating on Exhaust Valve Stress

According to Table 4. 6 and Table 4. 7, effect ceramic coating on exhaust valve is the stress increased along with the increase of coating thickness. Exhaust valve with 0.3mm ceramic coating has the lowest stress with a value of 353.26 MPa. Meanwhile, stress on ceramic coating is decreased along with the additional thickness of the coating. But in overall, stress distribution on non-coated exhaust valve and coated exhaust valve are similar, the highest stress occurs seat face area.

5.4. Recommendation

1. Tensile load might be used to produce stress on the valve stem.
2. Boundary load variation based on engine rotation and engine power output might be used.
3. Use testing result on UTM (Universal Testing Machine) to validate the simulation results.
4. Engine test should be considered to know the effect of ceramic coating on diesel engine performance.

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ATTACHMENT 1 – EXHAUST VALVE 3D FORM

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ATTACHMENT 2 – MATERIAL PROPERTIES

2.1. Nimonic 80A

Special Metals NIMONIC® Alloy 80A

Categories: Metal; Nonferrous Metal; Nickel Alloy; Superalloy

Material Notes: A nickel-chromium alloy similar to NIMONIC alloy 75 but made precipitation hardenable by additions of aluminum and titanium. The alloy has good corrosion and oxidation resistance and high tensile and creep-rupture properties at temperatures to 1500°F (815°C). Used for gas-turbine components (blades, rings, and discs), bolts, tube supports in nuclear steam generators, die-casting inserts and cores, and exhaust valves in internal-combustion engines. Standard product forms are round, hexagon, flats, extruded section, tube, plate, sheet, and wire.

Data provided by the manufacturer, Special Metals.

Key Words: Nickel-Chromium Alloy; UNS N07080; BS 3076 (NA 20), HR1, HR201, HR401, HR601; ASTM B 637; DIN 17742, 17754, Werkstoff Nr. 2.4952, 2.4631; WL Nr. 2.4631, AFNOR NC 20TA; AECMA Pr EN 2188 - 2191, 2396, 2397

Vendors: **Click here to view all available suppliers for this material.**

Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	8.19 g/cc	0.296 lb/in³	

Mechanical Properties	Metric	English	Comments
Tensile Strength, Ultimate	1030 MPa @Temperature 650 °C	149000 psi @Temperature 1200 °F	Precipitation Hardened prior to test
	1250 MPa @Temperature 23.0 °C	181000 psi @Temperature 73.4 °F	
Tensile Strength, Yield	780 MPa @Strain 0.200 %	113000 psi @Strain 0.200 %	Precipitation Hardened. Value at room temperature
	710 MPa @Strain 0.200 %, Temperature 650 °C	103000 psi @Strain 0.200 %, Temperature 1200 °F	Precipitation Hardened prior to test
Elongation at Break	30 %	30 %	Precipitation Hardened
	30 % @Temperature 650 °C	30 % @Temperature 1200 °F	Precipitation Hardened prior to test.

Electrical Properties	Metric	English	Comments
Electrical Resistivity	0.000124 ohm-cm	0.000124 ohm-cm	
Magnetic Permeability	1.0006	1.0006	at 200 oersted (15.9 kA/m)

Thermal Properties	Metric	English	Comments
CTE, linear	12.7 µm/m-°C @Temperature 20.0 - 100 °C	7.06 µin/in-°F @Temperature 68.0 - 212 °F	
Specific Heat Capacity	0.448 J/g-°C	0.107 BTU/lb-°F	
Thermal Conductivity	11.2 W/m-K	77.7 BTU-in/hr-ft²-°F	
Melting Point	1320 - 1365 °C	2410 - 2489 °F	
Solidus	1320 °C	2410 °F	
Liquidus	1365 °C	2489 °F	

Component Elements Properties	Metric	English	Comments
Aluminum, Al	1.0 - 1.8 %	1.0 - 1.8 %	
Boron, B	<= 0.0080 %	<= 0.0080 %	
Carbon, C	<= 0.10 %	<= 0.10 %	
Chromium, Cr	18 - 21 %	18 - 21 %	
Cobalt, Co	<= 2.0 %	<= 2.0 %	
Copper, Cu	<= 0.20 %	<= 0.20 %	
Iron, Fe	<= 3.0 %	<= 3.0 %	
Manganese, Mn	<= 1.0 %	<= 1.0 %	
Nickel, Ni	69 %	69 %	As remainder
Silicon, Si	<= 1.0 %	<= 1.0 %	
Sulfur, S	<= 0.015 %	<= 0.015 %	
Titanium, Ti	1.8 - 2.7 %	1.8 - 2.7 %	
Zirconium, Zr	<= 0.15 %	<= 0.15 %	

2.2. Ceramic Si_3N_4

CeramTec SL 200 ST Silicon Nitride, Si3N4-Y2O3

Categories: Ceramic; Nitride

Material Notes: SL 200 ST is a silicon nitride ceramic especially suitable for components exposed to mechanical stress and engine-specific applications even at elevated temperatures. It is recognized for its high strength and crack resistance, as well as its resistance to sudden changes in temperature. In contrast to the other silicon nitride materials, this is a gas-pressure sintered Si3N4 and hence possesses much better mechanical properties such as greater flexural strength, fracture toughness, and a higher Weibull modulus.

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	3.21 g/cc	0.116 lb/in³	DIN EN 623-2 / ASTM-C373 / ASTM-C20
Water Absorption	0.00 %	0.00 %	DIN EN 623-2 / ASTM-C373
Permeability	0.00	0.00	Gas
Weibull Modulus	15	15	DINV ENV 843-5

Mechanical Properties	Metric	English	Comments
Vickers Microhardness	1500	1500	HV 0.5; DINV ENV 843-4
Tensile Strength at Break	750 MPa	109000 psi	ACMA Test #4 / DIN EN 843-1
Tensile Modulus	305 GPa	44200 ksi	Young's; DINV ENV 843-2 / ASTM-F417
Flexural Strength	900 MPa	131000 psi	DIN EN 843-1
Compressive Strength	3000 MPa	435000 psi	ASTM C-773-88 / DIN 51067T1
Poissons Ratio	0.26	0.26	DINV ENV 843-2
Fracture Toughness	7.00 MPa-m½	6.37 ksi-in½	DIN 51109
Shear Modulus	121 GPa	17500 ksi	Calculated

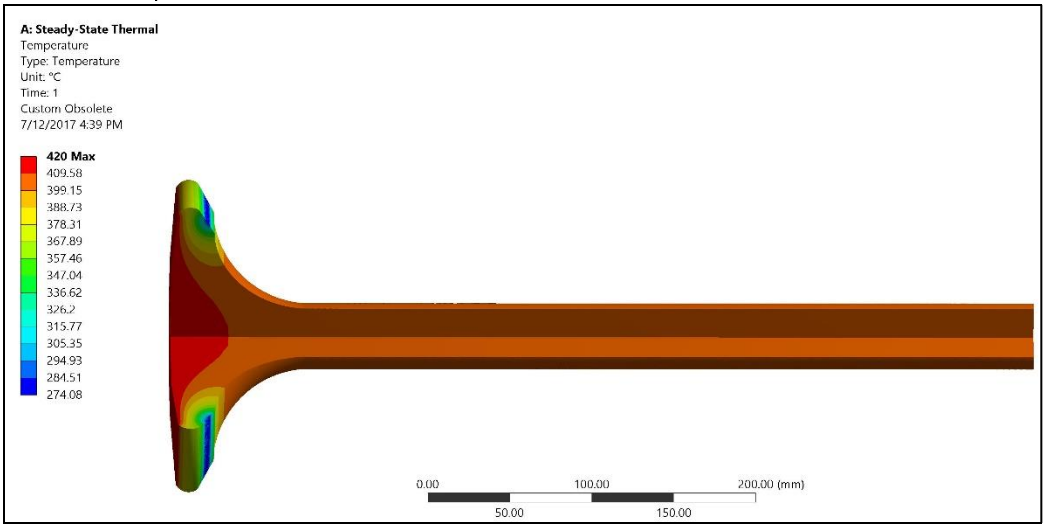
Electrical Properties	Metric	English	Comments
Volume Resistivity	1.00e+14 ohm-cm	1.00e+14 ohm-cm	ASTM-D257
Dielectric Constant	8.0 @Frequency 1.00e+6 Hz	8.0 @Frequency 1.00e+6 Hz	IEC 672-1 / ASTM-C150
Dielectric Loss Index	0.00010 @Frequency 1.00e+9 Hz	0.00010 @Frequency 1.00e+9 Hz	IEC 672-1 / ASTM-D149,150

Thermal Properties	Metric	English	Comments
CTE, linear	3.20 µm/m-°C @Temperature 20.0 - 200 °C	1.78 µin/in-°F @Temperature 68.0 - 392 °F	DIN EN 821-1
	4.30 µm/m-°C @Temperature 20.0 - 1000 °C	2.39 µin/in-°F @Temperature 68.0 - 1830 °F	DIN EN 821-1
Specific Heat Capacity	0.700 J/g-°C @Temperature 100 - 200 °C	0.167 BTU/lb-°F @Temperature 212 - 392 °F	DINV ENV 821-3
Thermal Conductivity	21.0 W/m-K @Temperature 20.0 - 100 °C	146 BTU-in/hr-ft²-°F @Temperature 68.0 - 212 °F	DIN EN 821-2 / ASTM-C408
Maximum Service Temperature, Air	1300 °C	2370 °F	
Maximum Service Temperature, Inert	1600 °C	2910 °F	

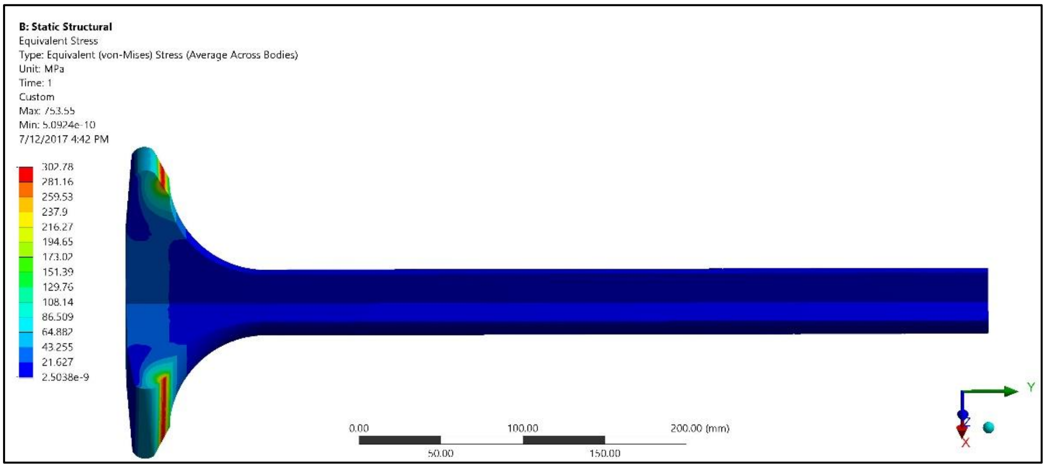
ATTACHMENT 3 – SIMULATION RESULT

4.1. Non-Coated

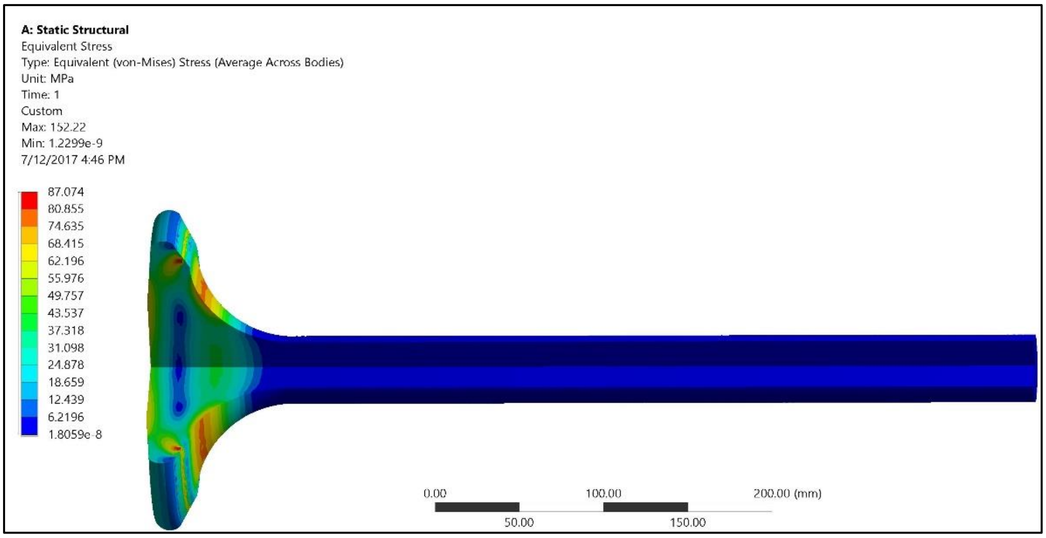
4.1.1. Temperature distribution



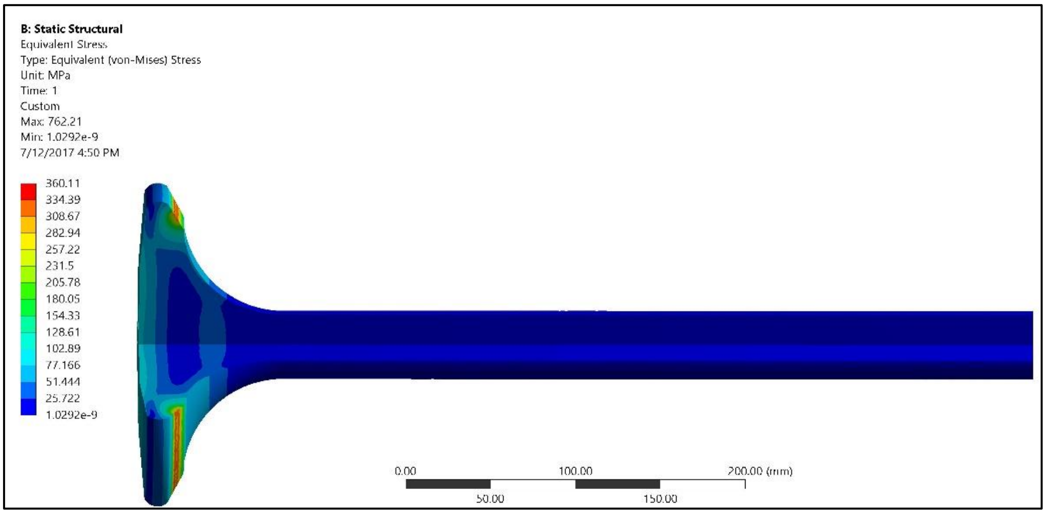
4.1.2. Thermal stress



4.1.3. Mechanical stress

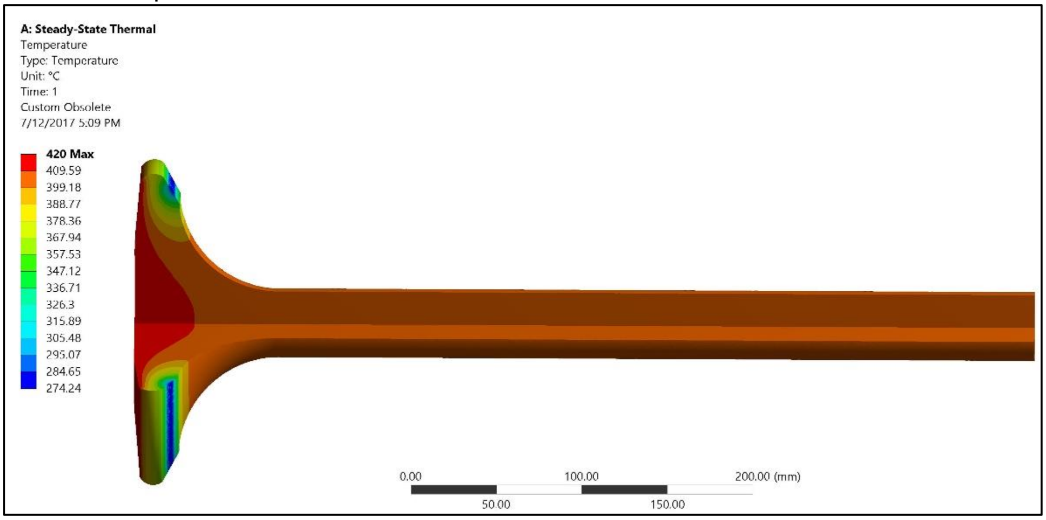


4.1.4. Thermo-mechanical stress

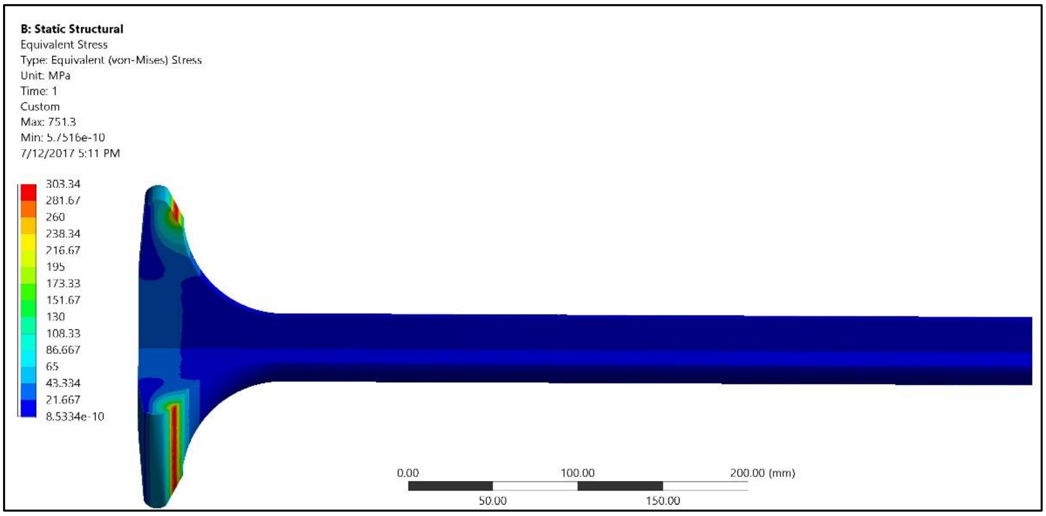


4.2. 0.3mm Coated

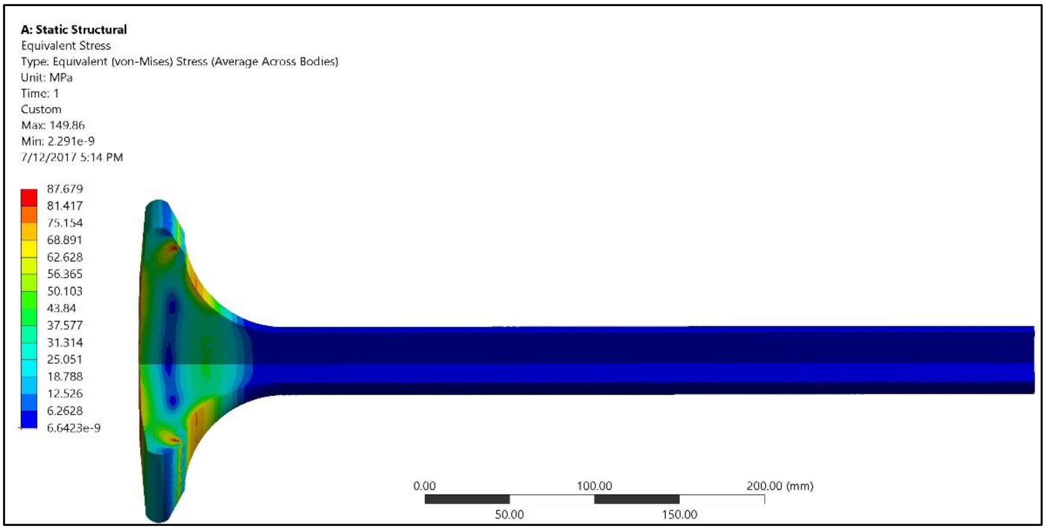
4.2.1. Temperature distribution



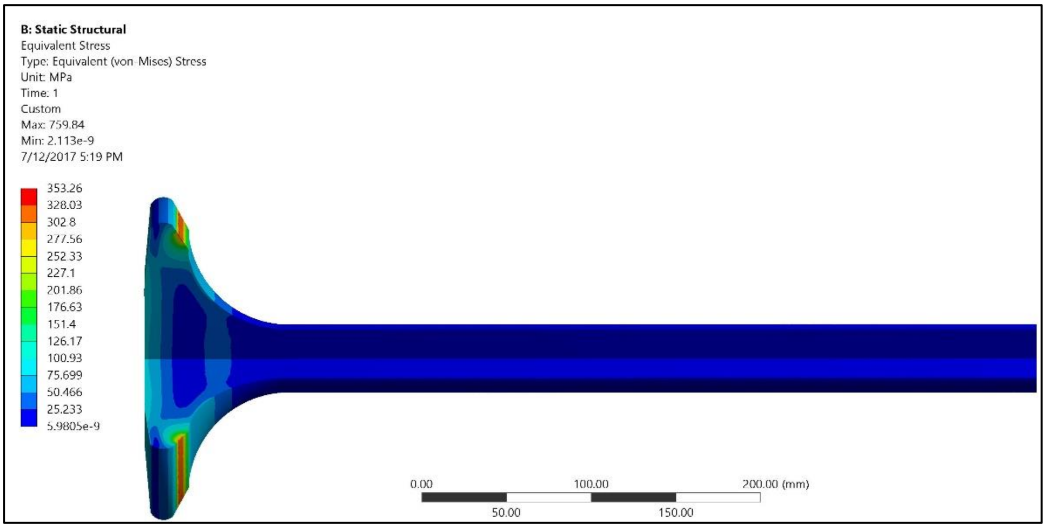
4.2.2. Thermal stress



4.2.3. Mechanical stress

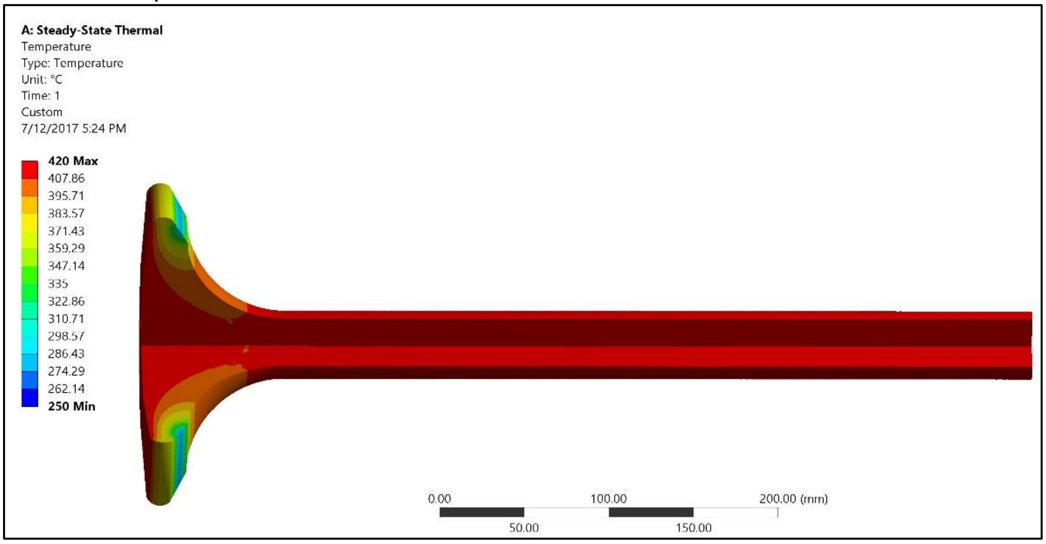


4.2.4. Thermo-mechanical stress

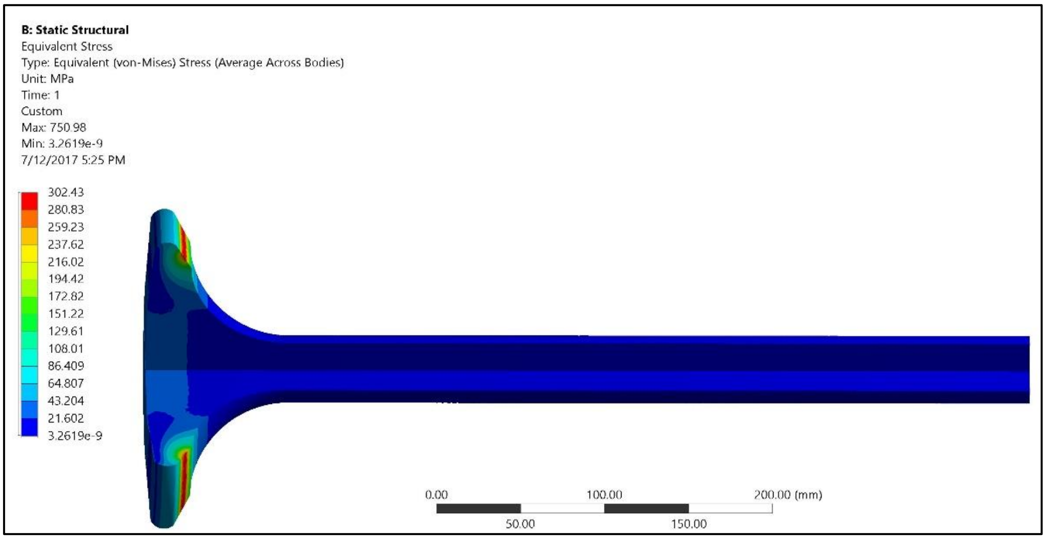


4.3. 0.4mm Coated

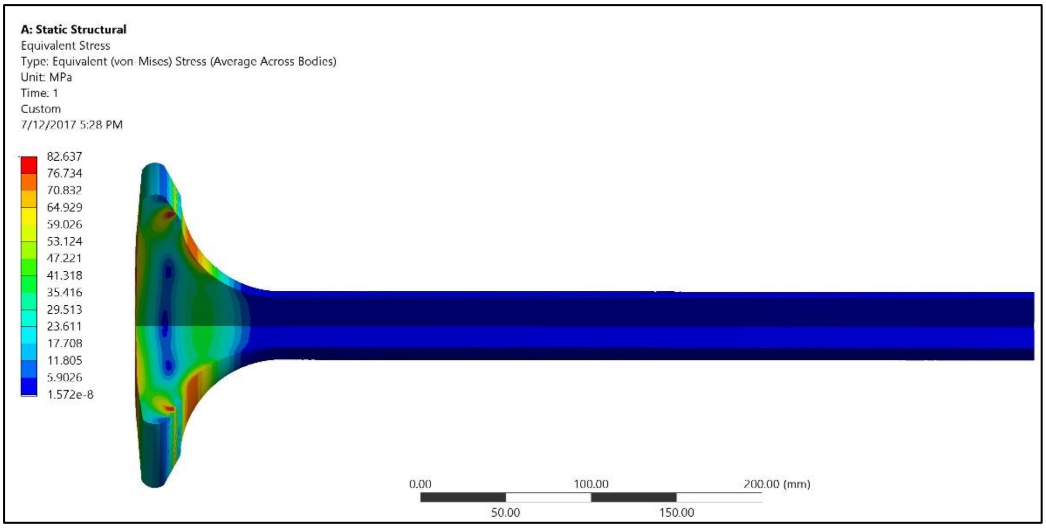
4.3.1. Temperature distribution



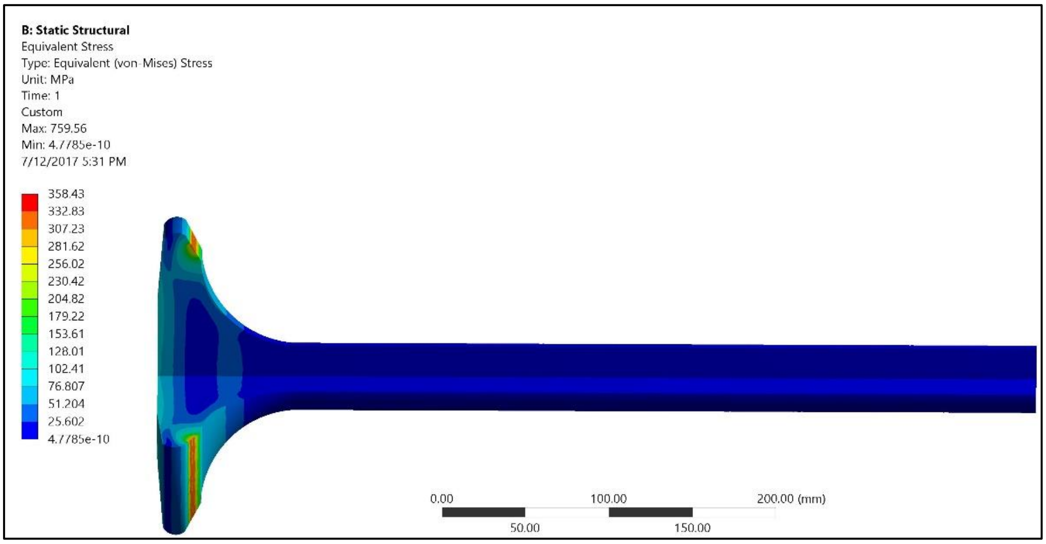
4.3.2. Thermal stress



4.3.3. Mechanical stress

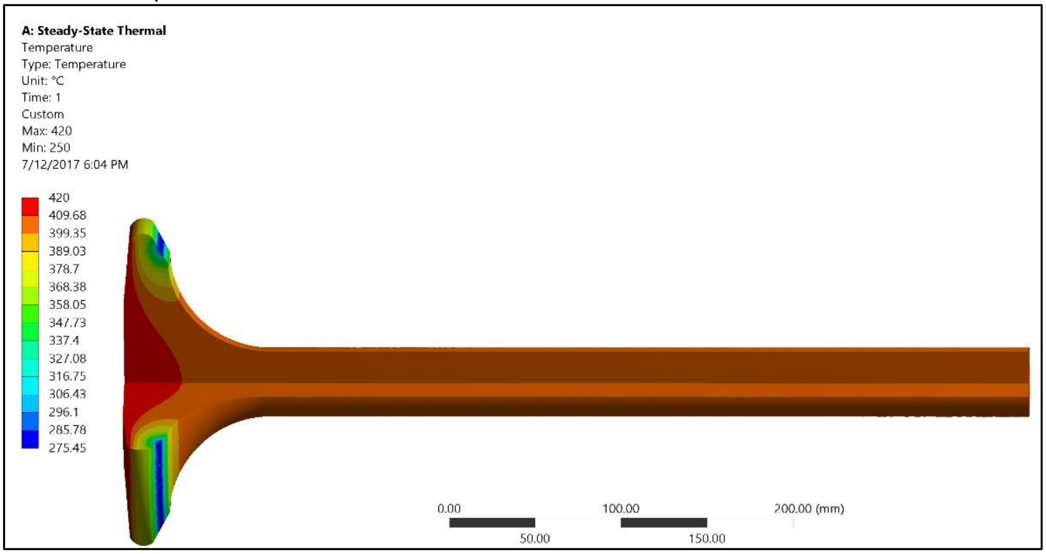


4.3.4. Thermo-mechanical stress

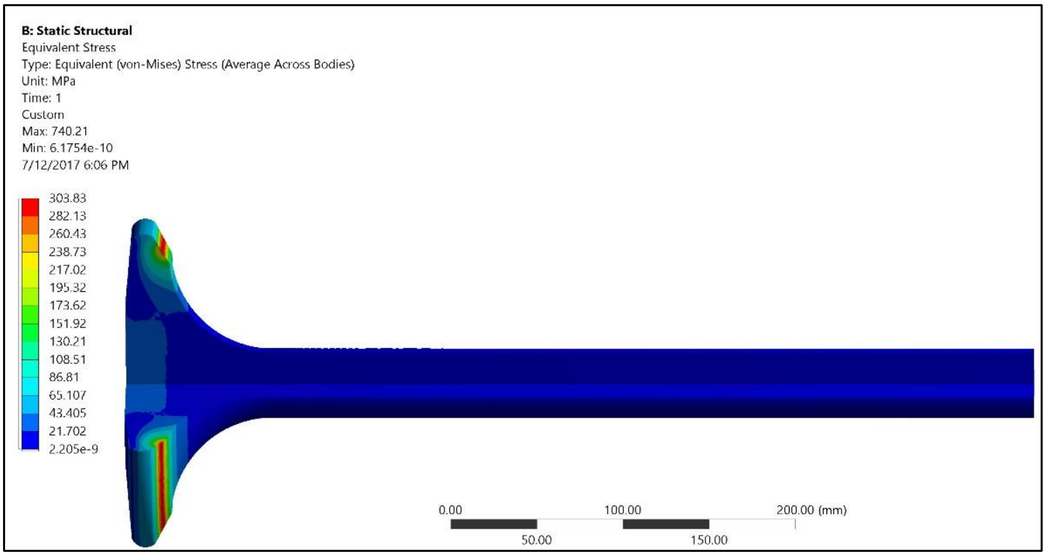


4.4. 0.5mm Coated

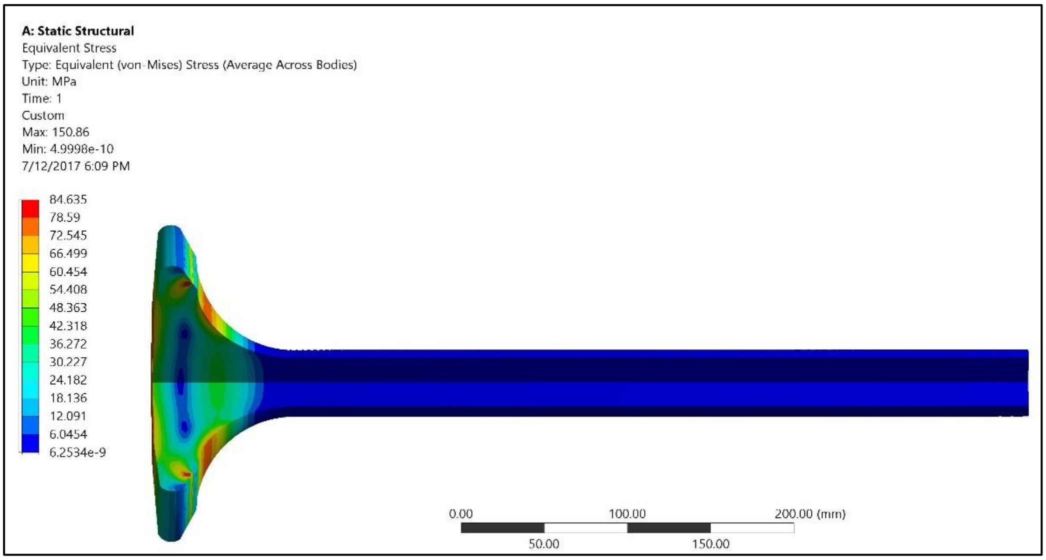
4.4.1. Temperature distribution



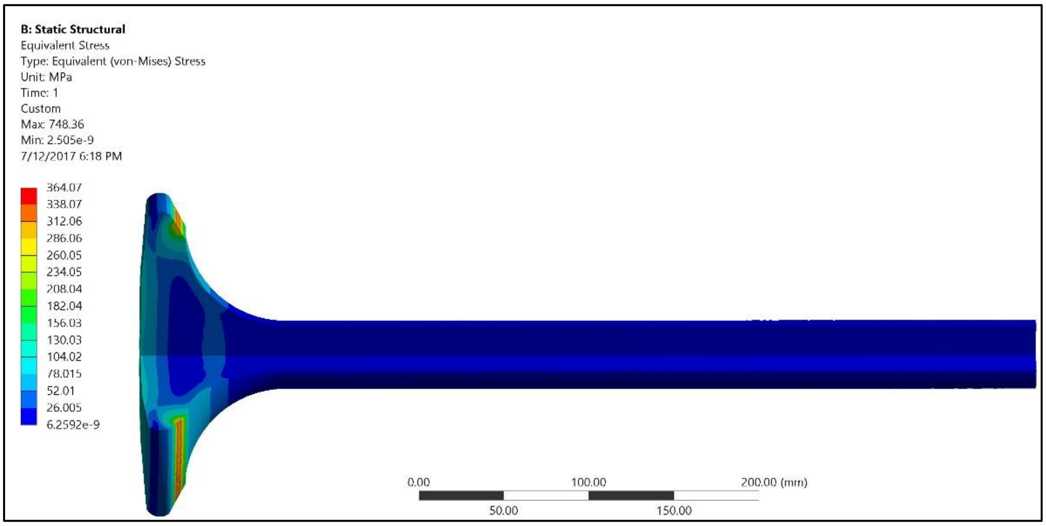
4.4.2. Thermal stress



4.4.3. Mechanical stress



4.4.4. Thermo-mechanical stress



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Motto: Think it, do it, finish it.